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Publication date:
2015

Document Version
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Citation (APA):
Mischke, P. (2015). *China's "energy revolution": measuring the status quo, modelling regional dynamics and assessing global impacts*. DTU Management Engineering.

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China's "energy revolution": measuring the status quo, modelling regional dynamics and assessing global impacts

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March 2015

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Thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy at the Technical University of Denmark.

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The different studies, associated conference presentations and website blog entries are also electronically available from the following website:

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Summary

As the world's largest economy in transition, China plays a growing role in global energy markets, clean technology deployment and climate change negotiations. The Chinese president Xi Jinping called in June 2014 for an "energy revolution" of the country's "energy production and consumption habits in light of changing dynamics in global energy markets" [Xinhua, 2014]. This highlights the strategic importance of China's energy sector in the country's national economic planning and its associated global impacts. China furthermore has a growing research and development budget and plays an increasing role in global scientific collaboration networks. A wide range of Chinese national and provincial statistics builds the foundation of this China energy sector research and allows measuring and modelling its main regional dynamics. As the quality, reliability, and availability of China's official statistics continues to be critically debated in the scientific community, additional complexity gets introduced to many China-specific research areas, such as the ones discussed here.

This research takes thus place in a fascinating, highly complex and fast-paced research environment. The overall aim of this PhD thesis is to describe and discuss the main characteristics China's "energy revolution" by means of (i) measuring and quantifying the status quo of China's energy sector with a focus on major regional characteristics, (ii) modelling selected future scenarios for different regions of China, and (iii) benchmarking and visualizing associated global impacts of China's "energy revolution". The general framework of investigation was chosen as a cross-disciplinary and highly collaborative approach. Different quantitative-based, economic, technical, and financial planning tools are developed, expanded and applied in this regard. The theories underlying this research are stemming from various scientific disciplines, such as energy and power engineering, macro- and energy-economics, and power project finance. Cross-cutting aspects are the harmonization of Chinese and international energy statistics and the communication of complex scientific results for a broad scientific and public audience.

Novel scientific approaches and results of this research include: (i) a pragmatic methodology development to construct regional energy balances for China in the format of a commonly used international energy balance; (ii) a review and benchmarking exercise of 18 Chinese energy modelling tools followed by a discussion of the Chinese perspective towards a low-carbon economy; (iii) an energy system wide mapping of regional energy flows in China to evaluate main disparities; (iv) a coupling of two complex top-down and bottom-up global energy planning tools to model future regional dynamics of China's energy sector; and (v) an assessment of electricity generation costs of the first operational concentrated solar power technologies in China. The results of this thesis are relevant for a broad scientific and public audience interested in an overview of China's ongoing energy and power system transition. The transparent, collaborative, and cross-disciplinary approach of this research allows gaining a deeper understanding of China's "energy revolution" from various economic, technical and financial perspectives, while highlighting associated complexities, such as data challenges.

总结 – Summary in Chinese

作为世界最大的发展中经济体，中国在全球能源市场和国际气候谈判中扮演着越来越重要的角色。**国家主席**习近平在**2014年6月的中央**财经领导小组会议中提出，必须推动能源生产和消费革命，形成主要由市场决定能源价格的机制 （**新**华社，2014）。这加强了能源部门在全国经济规划和相关国际影响中的重要性。另外，中国也在增加科研研发预算和增强国际科研合作中的地位。大量的国家和省级统计构建了重要能源部门的数据计量和建立区域动态的基础。由于中国官方统计数据的质量、可靠性和可用性在学术界被怀疑和讨论，这为中国相关的研究课题带来了额外的复杂性。

所以本文处在前沿、高度复杂的和快节奏的研究领域中。本论文的目的是在以下几个方面描述和讨论中国的"**能源革命**"： (i) 测量和量化中国能源系统并集中讨论主要的区域特色，(ii) **模**拟中国能源部门的未来情景并集中讨论**国内各区域的**动态变化，(iii) **基准化和可**视化中国"**能源革命**"**的全球影响。**论文的总体框架采用了跨学科和高度协作的方式，并开发了不同的经济，技术和财务规划工具。本研究的理论基础由不同学科理论组成，例如能源与动力工程，宏观和能源经济学和电力项目融资。中国和国际能源统计的协调，以及复杂的科学成果和公众之间的沟通是本研究的交叉研究方面。

本文的创新点和研究结果包括：(i) **采用**务实的方法，按照国际上常用的能源平衡表的方式构建了中国分地区能源平衡表; (ii) 对**18个中国能源建模工具**进行了文献综述和基准设定，并对中国国内对于低碳经济的视角进行了讨论； (iii)**在中国能源系**统范围内的利用能流图来形容当前的各区域能源系统的不同; (iv) **整合了两个复**杂的自上而下和自下而上的全球能源规划模型，从全球角度模拟了中国的能源行业未来的区域动态耦合；(v) 计算了中国的聚光太阳能发电厂的发电成本和对未来的技术前景进行了讨论。论文的结论契合了科学界和公共的中国正在进行的能源和动力系统的转型。这项研究的透明，协作和跨学科的方法让我们从各种经济，技术和财政的角度对中国的"**能源革命**"**有了更深的**认识，同时强调相关的复杂性和不确定性，**如**统计问题。

Populært dansk resume – Summary in Danish

Som verdens største økonomi under forandring, spiller Kina en stigende rolle på de globale energimarkeder og ved internationale klimaforandrings forhandlinger. Den kinesiske præsident, Xi Jinping, efterspurgte i juni 2014 en "energi revolution" for landets "energiproduktion og forbrugsadfærd i lyset af skiftende dynamikker på de globale energi markeder" [Xinhua, 2014]. Dette understreger den strategiske vigtighed af Kinas energisektor i den nationale økonomiske planlægning og den tilsvarende globale effekt. Herudover har Kina et stigende forsknings- og udviklings budget og spiller en voksende rolle i globale netværk af forskningssamarbejder. En bred vifte af Kinas nationale og regionale statistik bygger på grundstenene af denne forskning og tillader måling og modellering vigtige regionale dynamikker i Kinas voksende energi sektor. Eftersom kvaliteten, pålideligheden og tilgængeligheden af Kina officielle statistikker til stadighed bliver kritisk debatteret i det videnskabelige sektor, bliver stigende kompleksitet introduceret til alle Kina-specifikke forskningsområder.

Denne forskning folder sig derfor ud i et fascinerende, meget komplekst og hastigt udviklende forsknings miljø. Det overordnede mål for denne Ph.d. afhandling er at beskrive og diskutere hoved karakteristikaende af Kinas "energi revolution" ved at, (i) måle og kvantificere status quo for Kinas energi systemer med fokus på regionale karakteristika, (ii) modellere udvalgte fremtidige scenarier for Kinas energisektor med fokus på regionale dynamikker inden for Kina, og (iii) benchmarke og visualisere den globale betydning af Kinas "energirevolution". De generelle rammer for projektet er valgt ud fra et interdisciplinært perspektiv med høj grad af samarbejde. Forskellige økonomiske, tekniske og finansielle planlægnings værktøjer er udviklet i denne forbindelse. Den underliggende teori bag forskningen stammer fra en række forskellige discipliner, såsom energi og kraft ingeniørvidenskab, makro- og energi økonomi, samt kraft-projekt finansiering. Det interdisciplinære aspekt udtrykker sig ved harmoniseringen af den Kinesiske og internationale energi statistik, samt kommunikation af komplekse videnskabelige resultater til et bredt publikum.

Nye forskningsvinkler og resultater af denne afhandling inkluderer: (i) en pragmatisk metodologi til at konstruere sub-nationale (regionale) energibalancer for Kina i form af en alment benyttet international energi balance; (ii) en overblik- og benchmarking øvelse for 18 kinesiske energi modelleringsværktøjer efterfulgt af en diskussion af det kinesiske perspektiv af en lav CO2 økonomi; (iii) et bredt energisystemisk kort over regionale energistrømme i Kina til at beskrive regionale energi systemiske forskelle; (iv) en sammenlægning af to komplekse 'top-down' og 'bottom-up' globale energi planlægningsværktøjer til at modellere dynamikkerne i Kinas fremtidige regionale energisektor i et internationalt perspektiv; og (v) en udregning af produktionsomkostningerne for elektricitet skabt af solenergi kraftværker i Kina og en diskussion a fremtidige teknologiske perspektiver. Resultaterne a denne afhandling er relevante for et bredt videnskabeligt og offentligt publikum med interesse i Kinas igangværende energi og kraft systems forandringer. Den gennemsigtige, samarbejdende og interdisciplinære vinkel i denne afhandling fører til en dybere forståelse af Kinas "energi revolution" fra forskellige økonomiske, tekniske og finansielle perspektiver, alt i mens den understreger de tilknyttede kompleksiteter og usikkerheder, så som statistiske udfordringer.

Acknowledgments

在家靠父母，在外靠朋友. At home one relies on parents, away from home one relies on friends.

Old Chinese proverb.

This PhD thesis concludes an intensive three year research period I spent in Denmark and China, two new countries I enjoyed exploring and living in as a foreign researcher. The work presented here was carried out under the general direction of Prof. Yi WANG, Chinese Academy of Sciences, Institute of Policy Management and Kenneth KARLSSON, PhD, Technical University of Denmark, Energy Systems Analysis Group. I like to thank both of them for giving me their support and allowing me the professional freedom to start this new Sino-Danish energy research collaboration. I visited different parts of China during four research stays and would like to thank furthermore all Chinese colleagues from the Tsinghua University's Institute of Energy, Environment and the Economy, under the direction of Prof. Xiliang ZHANG; the Chinese Academy of Sciences' Institute of Policy Management under the direction of Prof. Yi WANG; and the Chinese Academy of Sciences' Centre for Energy and Environmental Policy Research under the direction of Prof. Fan YING for hosting me as a visiting PhD scholar on these occasions. I am also thankful for the continuous support of all my colleagues at Energy Systems Analysis Group in Denmark.

Special thanks go to all my co-authors: Hancheng DAI, Kenneth KARLSSON, Toshohiko MASUI, Asami MIKETA, Nicholas WAGNER, Xuxuan XIE, Weiming XIONG, Da ZHANG & Zhao ZHU. It was a great pleasure working with all of you on these exciting China energy topics.

The results presented here benefitted tremendously from my personal exchanges with various Chinese and international energy sector colleagues I met during this journey. I’d like to thank furthermore the following colleagues for sharing their China-specific energy sector insights with me: African Development Bank (Jing LI); Asian Development Bank (Shigeru YAMAMURA & Terushi OI); Aalborg University Denmark (Wen LIU); the Asia Banker (Gerlinde GERBER); Chinese Academy of Sciences (Yi WANG, Ying FAN, Wu XIE, Xiuping ZHOU, Xingjun RU & Qin HAIBO); China National Renewable Energy Centre (Kaare SANDHOLT); Climate Wire Asia (Coco LIU); Copenhagen Capacity (Xiuqing JI & Guo LI); Danish Energy Agency (Marianne NIELSON & Niels BISGAARD PEDERSEN); Danish Embassy Beijing (Christian VAN MAARSCHALKERWEERD); DTU UNEP partnership, formerly UNEP RISO (Xianli ZHU, Xiao WANG, Daniel PUIG & Soren LUETTKEN); Energianalyse Denmark (Lars BREGNBAEK); Energy Crossroads Denmark (Yongbiao WEN & Alison MAN); Energy Sector Management Assistance Program (Emmanuel PY); Ecofys China (Maarten NEELIS & Carlos CASANOVA); European Chamber of Commerce Shanghai (Tiantian QI); Fraunhofer Joint Centre for Innovation Research China (Ulrike TAGSCHERER); German Technical Cooperation China (Till KOETTER, Amber SHARIK & Paul RECKNAGEL); International Energy Agency (Jianjun TU, Shuwei ZHANG, Uwe REMME & Fabian KESICKI); Energy Technology Systems Analysis Program (Sokrates KYPREOS, Mauricio GARGULIO & Gary GOLDSTEIN); International Energy Conservation Environmental Protection Association

China (Zhichao LI); International Renewable Energy Agency (Deger SAYGIN, Yong CHEN, Asami MIKETA & Michael TAYLOR); King Abdullah Petroleum Studies and Research Center Saudi Arabia (Brian ERFID & Nicolas HOWARTH); MERCATOR Institute for China Studies Germany (Elena KLORER, Jost WUEBBEKE & Mirjam MEISSNER), MIT Tsinghua China Energy & Climate Project (Xiliang ZHANG, Valerie KARPLUS, Da ZHANG & Paul N. KISHIMOTO); National Institute of Environmental Studies Japan (Hancheng DAI & Toshihiko MASUI); Energy Research Institute China (HAN Wenke, Kejun JIANG, Xuxuan XIE, Tao YE, An QI & Jingjing YIN); Pacific Northwest National Laboratory USA (Catherine CALVIN & Jason EDWARDS); Potsdam Institute for Climate Impact Research Germany (Jan MINX); Remnin University China (Xueqin CUI, Yue XIN & Junling LIU); Sino-Danish Center for Innovation and Research Denmark (Lars CHRISTENSEN & Na LIN); Sino-Danish Centre for Education and Research (Martin BECH & Morten LAUGESEN); Technical University of Berlin Germany (Felix CREUTZIG); Technical University of Denmark (Gaoming DAI, Manlong XIA, Guangya YANG & Xiadan ZHANG); Tsinghua University China (Jing CAO, Wenjing CHEN, Xiang YIN, Jingchen SHI, Xiaohan ZHANG, Weiming XIONG, Tianyu QI, Tao WANG, Benjamin DESJEAN & Cyril CASSIA); University of Cambridge UK (Zhu ZHAO); University of Copenhagen Denmark (Jorgen DELMAN & Magnus JOREM); University of Berkeley China Energy Group USA (Gang HE, Lixuan HONG & Ali HASANBEIGI); University of Maryland USA (Kuishuang FENG); Technical Research Centre of Finland (Quan JIN); Xiamen University China (Hongxia DUAN); and World Bank Group (Xiaodong WANG, Peter COOK, William BELOE, Emmanuel PY & Luiz MAURER). I hope we will find many more occasions to continue our exchanges in the future.

Last but not least, I am very thankful for all the support I enjoyed on the private level, from my family as well as "old" and "new" friends, in Europe and in China. This journey has been truly amazing and full of new stories and experiences, that I will remember deeply. 谢谢大家！

Funding sources

I would like to acknowledge the generous financial support that I received for the preparation of this thesis as well as the participation in several international energy conferences. Funding sources are: (i) the Sino-Danish Centre for Education and Research; (ii) Idella Fonden Denmark; (iii) the Technical University of Denmark; (vi) the International Energy Agency's Energy Technology Systems Analysis Program; (v) the UK Energy Research Centre; (vi) the Groningen University Energy and Sustainability Program Netherlands and (vii) the German Volkswagen Foundation.

Additional support was received through my collaborations with Tsinghua University, the National Institute of Environmental Studies of Japan (NIES) and the International Renewable Energy Agency (IRENA): (i) the Shandong Collaborative Innovation Centre of Energy Economy China; (ii) the Science Foundation of Ministry of Education of China and (iii) Rio Tinto through Tsinghua University's Institute for Energy, Environment, and Economy; (iv) ENI Italy, (v) ICF International and (vi) Royal Dutch Shell through the Tsinghua University MIT China Energy and Climate Project; (vii) the Strategic Research Centre for 4th Generation District Heating Denmark; (viii) the Environment Research and Technology Development Fund of the Ministry of the Environment of Japan; and (ix) the IRENA Renewable Energy Roadmap Project, ReMAP 2030.

Disclaimer

This research is carried out in a fast-moving and highly complex research area, any omissions and errors are solely those of the author. The opinions expressed and arguments employed in this thesis do not necessarily reflect the official views of the funding and collaborating institutions.

Any map of the People's Republic of China and regional definitions of China applied here are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Complete list of PhD Publications

Parts of this PhD thesis have been or are going to be published as peer-reviewed academic journal articles, book chapters, conference and working papers. In addition various international energy conference presentations, contributions to research reports, and China-specific energy blog posts were prepared to establish and maintain a dialogue with a broad scientific and public audience. Two independent external expert reviews for the International Renewable Energy Agency (IRENA) and the German National Academy of Science and Engineering (acatech) were also carried out.

Seven peer-reviewed publications build an integral part of this thesis. These are marked with (Publication) below and are attached as appendices of this thesis.

Journal articles (peer-reviewed)

Hancheng DAI, **Peggy MISCHKE**, Xuxuan XIE & Toshihiko MASUI (2015), *Quantifying uncertainty in China's regional energy future towards 2050: a global model soft-linking and comparison exercise*, Applied Energy, forthcoming (Publication D)

Zhao ZHU, Da ZHANG, **Peggy MISCHKE** & Xiliang ZHANG (2015), *Electricity generation costs of concentrated solar power technologies in China based on operational plants*, Energy, forthcoming (Publication G)

Peggy MISCHKE & Weiming XIONG (2015), *Mapping and benchmarking regional disparities in China's energy supply, transformation and end-use in 2010*, Applied Energy, Volume 143, 1 April 2015, pages 359-369, doi.org/10.1016/j.apenergy.2015.01.011 (Publication C)

Peggy MISCHKE & Kenneth B. KARLSSON (2014), *Modelling tools to evaluate China's future energy system - a review of the Chinese perspective*. Energy, Volume 69, 1 May 2014, pages 132–143, doi:10.1016/j.energy.2014.03.019 (Publication B)

Hancheng DAI & **Peggy MISCHKE** (2014), *Future energy consumption and emissions in East-, Central- and West-China: Insights from soft-linking two global models*, Energy Procedia, Volume 61, pages 2584 – 2587, available online 12 January 2015, doi:10.1016/j.egypro.2014.12.253

Weiming XIONG, Da ZHANG, **Peggy MISCHKE** & Xiliang ZHANG (2014), *Impacts of Renewable Energy Quota System on China's Future Power Sector*, Energy Procedia, Volume 61, pages 1187 – 1190, available online 12 January 2015, doi:10.1016/j.egypro.2014.11.1050

Book chapters (peer-reviewed)

Peggy MISCHKE & Hancheng DAI (2015), *From global modelling to country analysis: focus on China with ETSAP-TIAM and AIM,* in: G. GIANNAKIDIS, M. LABRIET, B. Ó GALLACHOIR, G.C. TOSATO (Eds.), *Informing energy and climate policies using energy systems models. Insights from scenario analysis increasing the evidence base*, Springer, "Energy System" series, forthcoming (Publication F)

Kenneth B. KARLSSON, **Peggy MISCHKE**, Asami MIKETA & Nicholas WAGNER (2014), *Global energy perspectives with an emphasis on wind energy*, in: H. HVIDTFELDT LARSEN & L. SONDERBERG PETERSEN (Eds.), DTU International Energy Report 2014: *Wind energy — drivers and barriers for higher shares of wind in the global power generation mix*, Pages 19-25, Technical University of Denmark, ISBN: 978-87-550-3969-8, available at: http://orbit.dtu.dk (Publication E)

Conference papers and posters (peer-reviewed)

Peggy MISCHKE (2015). *Big data & China – Measuring the status quo of China's energy sector: Identifying opportunities and coping with data challenges*. Poster presented at the 7th Herrenhausen Conference: *Big Data in a Transdisciplinary Perspective*, Volkswagen Foundation Germany, Herrernhausen Palace, Hannover, Germany, 26 March 2015

Hancheng DAI, **Peggy MISCHKE**, Xuxuan XIE & Toshihiko MASUI (2014). *Future energy consumption, emissions and mitigation costs in East, Central and West China: Insights from soft-linking two global energy models*. Conference paper presented at the IEA ETSAP-UCC Workshop: Methodologies linking energy system models and global models, University College Cork, Cork, Ireland, 04 February 2014

Peggy MISCHKE (2013). *Regional and Global Energy System Modelling with focus on China*. Poster presented at the 2013 UK Energy Research Centre Annual Assembly Meeting and the 2013 UK Energy Research Centre international energy summer school, University of Warwick, Coventry, United Kingdom, 08 July 2013

Working papers and research reports

Poul E. GROHNHEIT, Kenneth B. KARLSSON, Olexandr BALYK, **Peggy MISCHKE**, Stefan PETROVIC, & Cristian H.C. PEREZ (2014), *Global and national TIMES models: Use of IEA-ETSAP TIMES models in Denmark*, Department of Management Engineering, Technical University of Denmark, 130 pages, available at: http://orbit.dtu.dk

Peggy MISCHKE (2014), *Improvements to ETSAP-TIAM Phase II: Improvements of China and related bugs*, Technical University of Denmark, 28 April 2014, technical note and electronic model files submitted to the Institute of Energy Economics and Rational Energy Use, University of Stuttgart, Germany, the ETSAP-TIAM Phase II coordinator

Peggy MISCHKE (2013), *China's energy statistics in a global context: A methodology to develop regional energy balances for East, Central and West China*. Technical University of Denmark, University of Munich open-access energy economics research repository MPRA, working paper nr. 50305, 44 pages, 01 October 2013, available at: http://mpra.ub.uni-muenchen.de/50305 (Publication A)

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List of figures of the PhD synopsis

Symbols and abbreviations

ADB	Asian Development Bank
AIM	Asian-Pacific Integrated Assessment Model
AME	Asia Modelling Exercise
BNEF	Bloomberg New Energy Finance
BU	bottom-up, a modelling framework
CAS	Chinese Academy of Sciences
CCS	Carbon Capture and Storage
CDB	China Development Bank
CEEP	Centre of Energy and Environmental Policy Research, Chinese Academy of Sciences
CGE	Computable General Equilibrium, a top-down model
CGNPC	China Guangdong Nuclear Power Corporation
CNREC	China National Renewable Energy Centre
CREAM	China Renewable Energy Analysis Model
CRESP	China Renewable Energy Scale-Up Program
CSP	Concentrated Solar Power
DoE	Department of Energy, United States of America
DRC	Development Research Centre, China
DTU	*Danske Tekniske Universitet*, Technical University of Denmark
ERI	Energy Research Institute, China
ETSAP	Energy Technology Systems Analysis Program, an implementing agreement of the IEA
EJ	Exa-Joule, 10^{18} Joule, a standardised international energy unit
FYP	Five-Year-Plan
GDP	Gross Domestic Product
GWEC	Global Wind Energy Council
ICNEA	Industrial Classification for National Economic Activities, China
IEA	International Energy Agency
IIASA	International Institute of Applied Systems Analysis, Austria
IO	Input-output, a top-down model framework
IPAC	Integrated Policy Assessment Model for China
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
ISIC	International Standard Industrial Classification, United Nations
LBNL	Ernest Orlando Lawrence Berkeley National Laboratory, United States of America
LEAP	Long-range Energy Alternatives Planning Model
LCOE	Levelized Costs Of Electricity
MARKAL	MARket Allocation model, a BU model framework
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MIT	Massachusetts Institute of Technology, United States of America
NBS	National Bureau of Statistics, China
NCEPU	North China Electric Power University, China

NDRC	National Development and Reform Commission, China
NEA	National Energy Administration, China
NGO	Non-Governmental Organisation
NIES	National Institute of Environmental Studies, Japan
NPC	National People's Congress, China
NPV	Net Present Value
NRDC	National Development and Reform Commission, China
NREL	National Renewable Energy Centre, United States of America
OECD	Organisation for Economic Co-Operation and Development
PBS	Provincial Bureau of Statistics, China
PNNL	Pacific Northwest National Laboratory, United States of America
POM	Portfolio Optimization Model, China
R&D	Research and Development
REmap	Renewable Energy Map, IRENA's 2030 global renewable energy road mapping exercise
RMB	Renminbi, the Chinese currency dominated in Yuan
RU	Renmin University, China
SC	State Council, China
SIC	State Information Centre, China
SI unit	standardised international unit
SL	soft-linked, a modelling framework
SSP	Shared Socio-economic Pathways
tce	tons of coal equivalent, a Chinese energy unit
TD	top-down, a modelling framework
TIAM	TIMES Integrated Assessment Model
TIMES	The Integrated MARKAL-EFOM System, a BU model framework
TOM	Technological Optimization Model, China
TU	Tsinghua University, China
TWh	Terra-Watt hours, 10^{12} Watt hours, a standardised international electricity unit
UCAS	University of the Chinese Academy of Sciences
UNFCCC	United Framework Convention to Combat Climate Change
USD	US Dollar, the currency of the United States of America
USTC	University of Science and Technology, China
WB	World Bank
WEO	World Energy Outlook, IEA's global energy scenario exercise

“Power of the powerless”[1]

Soon as you say do—you do.

Leave faster

than an angel flies, to

and fro. Your horizon's wide;

mine's narrow. See?

I can't even tell if you're into me.

I do it all and accomplish zero.

I'm not relaxed or free.

I still daydream of changing an era—

But I'm still powerless

and you must wait.

And if I fail, will you still want me?

You watch me silently.

Say nothing. Wordlessly

drop your hand to catch my hand

and hold it soft and tight.

Then you make it a fist,

raise it to your lips

and bite.

[1] 老崔. Cui Jian, 1998. Translated into English by Rachel de Woskin, available at: wordswithoutborders.org

Overview of contents

Detailed Table of Contents

1. Introduction

千里之行始于足下. The journey of a thousand miles starts with one step.

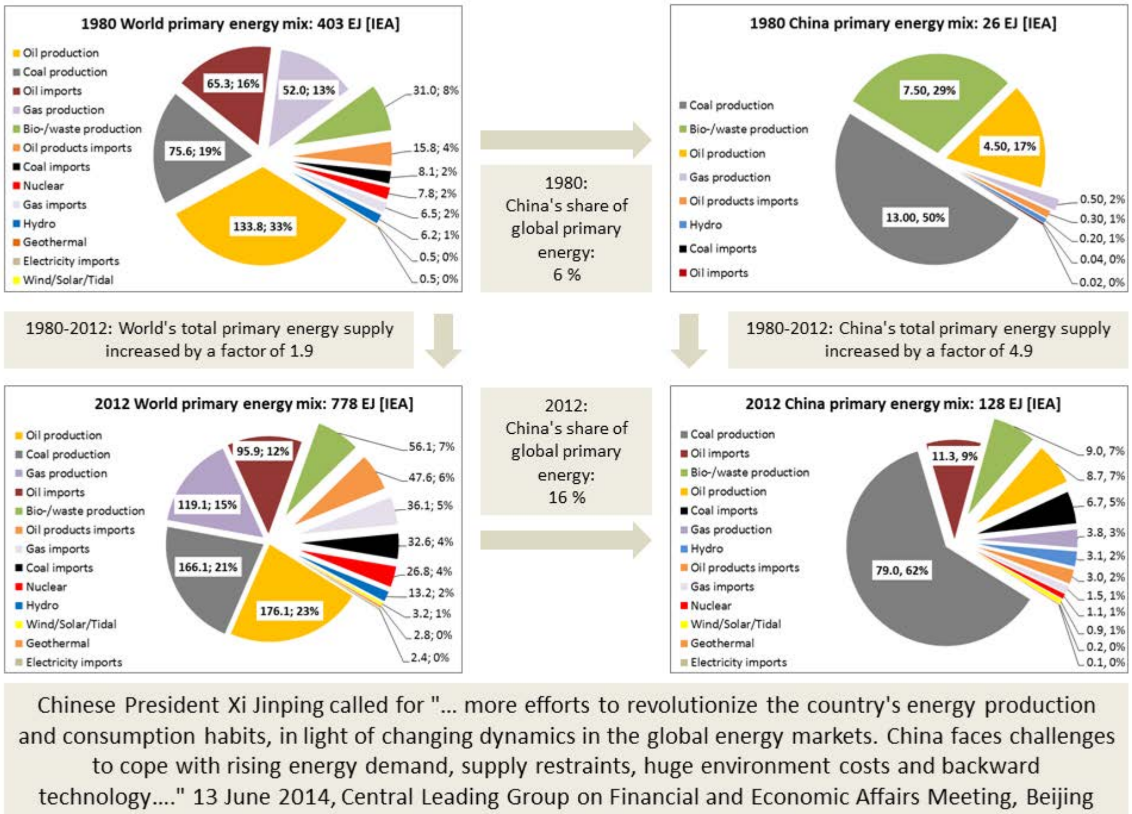
老子. Laozi, Chinese philosopher, 604-531 BC.

This chapter of the PhD synopses introduces the subject of investigation, China's "energy revolution". It introduces China's energy sector to a broad scientific and public audience by providing a few main energy statistics and recent press news. As this research is carried out in a new bilateral Sino-Danish energy research collaboration, it furthermore gives an overview of China's research culture and international research collaboration. The overall research aim is stated, current knowledge gaps are summarised, and specific research questions are developed to guide this research. The general framework of investigation is presented and the structure of this cumulative PhD report, consisting of a PhD synopsis and publication appendices, are explained.

1.1. Subject of investigation: China's "energy revolution"

The development, pace and scale of China's energy sector over the past three decades has been unprecedented globally. **Figure 1** highlights and compares a few key energy supply data for China and the World in this regard. The underlying data are available open-access from the International Energy Agency [IEA, 2012]. China's primary energy supply in **Figure 1** is defined as the sum of indigenous production, imports, exports and stock changes. For global primary energy supply international maritime and aviation bunkers are furthermore considered [IEA, 2012]. China's primary energy supply increased by a factor of 4.9 from about 26 EJ in 1980 to about 128 EJ in 2012. This represents an annual growth rate of about 8%, a much more rapid increase than the 5% global growth rate over the same period. Overall, China's share of global primary energy supply increased rapidly, from about 6% in 1980 to about 16% in 2012. The country's energy system thereby continues to rely heavily on coal. The share of domestic coal production in China's primary energy supply increased from about 50% in 1980 to about 62% in 2012. The non-coal share of China's primary energy mix diversified over the past three decades. Renewable energy sources, nuclear energy and domestic natural gas production are playing an increasing role. The share of fossil fuel imports, in particular oil and oil product imports increased. This is partly due to the decrease in China's domestic oil production, from about 17% of primary energy in 1980 to about 7% in 2012.

Figure 1: A snapshot of three decades of China's energy sector development (1980 – 2012).



Sources: energy supply from IEA; press news from Xinhua news agency [Xinhua, 2014], [IEA, 2012]

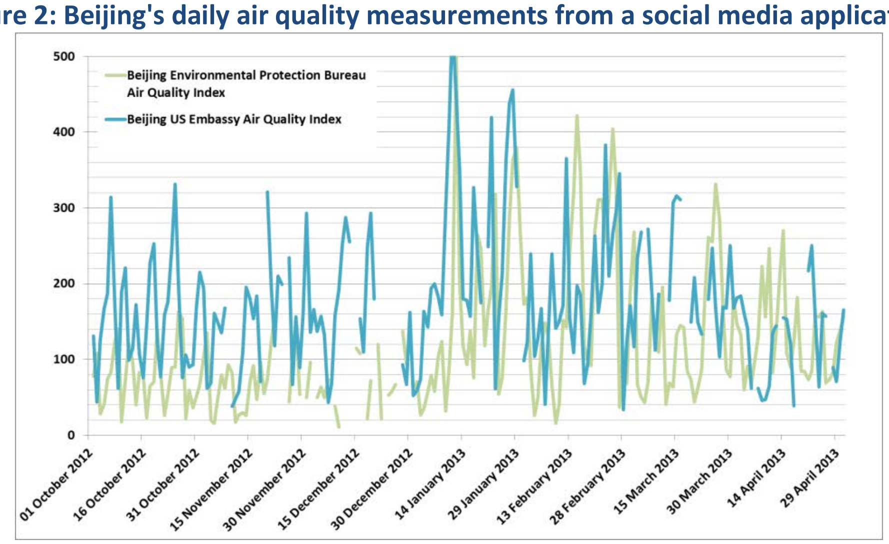
Various national and international news agencies report on the scale and the pace of China's ongoing energy sector expansion and associated global impacts. Recent press news in this regard include the following: Forbes reports that China invested more in renewable energy projects than all of Europe in 2013, estimated at a total of USD 473.1 billion for clean energy investments from 2011 to 2015 [FORBES, 2014]. Reuters interpreted China’s statement to cap the country’s CO_2 emissions in November 2014 as a turning point in global climate talks [REUTERS, 2014]. Greenpeace announced the end of China's coal boom based on its outlook on China’s provincial coal control measures towards 2020 [GREENPEACE, 2014]. Bloomberg New Energy Finance expected a doubling of China’s power capacity by 2030 which would require total power sector investments of USD 1.4 trillion. This was reported as an opportunity for renewables in new power plant investments and a choice to stop the dominant role of coal in the power sector [BNEF, 2013].

Challenges in understanding and assessing the quality and reliability of China’s economic, energy sector, and CO_2 emission are numerous. The following media statements give a few insights: The BBC reported on fake economic data in China due to the performance assessment of local government leaders [BBC, 2013]. The New York Times reported that Chinese data might hide the depth of the country’s economic slowdown, as evidence of falsified local and provincial economic statistics exists [NYT, 2012]. The Wall Street Journal reported that China's government disputed the International Energy Agency’s

(IEA) reporting that China surpassed the United States of America as the world's largest energy consumer in 2009 [WSJ, 2010]. The Guardian reported that Chinese websites and social media apps deleted the US embassy's air quality readings from their database after other measures fail to cut air pollution for a high level international Asia Pacific summit failed [GUARDIAN, 2014].

Understanding different air quality data for Beijing in presents one up-to-date example of the use of different statistical systems, which should be integrated into China-specific energy sector research. **Figure 2** maps daily air quality measurements collected by the PhD researcher in country from a Chinese social media application in 2013 [MISCHKE, 2013]. Beijing's daily air quality indices from the Environmental Protection Bureau of the Ministry of Environment of China and the Embassy of the United States are compared during October 2012 and April 2013. As both air quality indices include different air pollutants, different calculation methodologies and different monitoring sites in Beijing, this can results in diverging and confusing air quality ratings. There are days one index indicates the air quality as "hazardous" and the other one states "slightly polluted". Suitable methodologies that translate between the Chinese statistical system and the commonly used international statistical system will be assessed and developed as part of this research.

Figure 2: Beijing's daily air quality measurements from a social media application.



This research is thus focussing on a globally emerging, highly complex and fascinating subject of investigation: China's ongoing "energy revolution". The Chinese president Xi Jinping called in June 2014 for an "energy revolution to revolutionise the country's energy production and consumption habits, in light of changing dynamics in the global energy markets" [XINHUA, 2014]. This highlights the strategic importance of China's energy sector in the country's national economic planning and its associated global impacts from a recent Chinese perspective. The Chinese term "energy revolution" is interpreted and applied in this research in the philosophy of an overarching longer-term policy objective, which is envisioning a continuous transition of China's energy system in line with the developments of global energy markets. This research aims to contribute to this ongoing debate about China's energy future.

1.2. Chinese research culture and international collaboration

China's research funding has been growing to about USD163 billion in 2012, while reforms in budgeting, reporting and transparency are underway. SUN & CAO give a recent overview of the complex institutional landscape and the multiple research and development (R&D) programs behind China's central government R&D expenditure. They estimated China's R&D budget at USD163 billion[2] in 2012, equivalent to about 2% of the country's GDP and suggested further steps to increase the transparency, institutional accountability and international comparability of China's R&D reporting standards [SUN & CAO, 2014]. The requirement of R&D reforms is also highlighted by SHI & RAO, both professors at two of the most prestigious Chinese universities, Tsinghua University and Beijing University. They concluded in 2010 that the top-down approaches in China's R&D system mainly favoured a few powerful scientists with strong connections to high-level bureaucrats in charge of research funding allocations [SHI & RAO, 2010]. In this context, they concluded that China's future innovation capability would be hampered.

Global collaboration networks are emerging in science and China is playing an increasing role in those networks, while China – EU collaboration remain limited. More than 74000 scientific publications resulted from Chinese researchers' collaboration with foreign-based researchers in 2011, up from only 9000 in 1998. More than 22000 of these Chinese publications were co-authored with US-based R&D institutions, followed by Japan, Australia, Canada and Korea [OECD, 2013]. Scientific collaborations between EU countries and China remained rather low over the same period, as EU countries primarily increased their research collaborations with EU-based R&D institutions. In terms of quantity - measured as number of publications by country - China was ranked second after the US, while in terms of quality - measured as top cited papers by country - it lagged most OECD countries [OECD, 2013].

1.3. Research aim and knowledge gaps

Literature reviews and personal exchanges with Chinese energy sector experts indicated a main knowledge gap between the research area of regional energy system analysis for China and the research area of energy statistic. More in detail the research gaps identified during several research stays in China include: (i) a limited availability of internationally comparable energy system-wide studies with sub-national details of China; (ii) a limited availability of collaborative modelling exercises for China's future energy system in a longer term perspective, allowing to compare and benchmark different results calculated by different energy planning tools under a common, harmonised baseline; (iii) a lack of a comprehensive scientific review of the growing number of Chinese energy models and the associated

[2] in 2014 current US dollars

Chinese perspective towards a low-carbon development in China, and (iv) a limited availability of up to date, systematic and transparent methodologies to harmonise Chinese and commonly used international energy statistics.

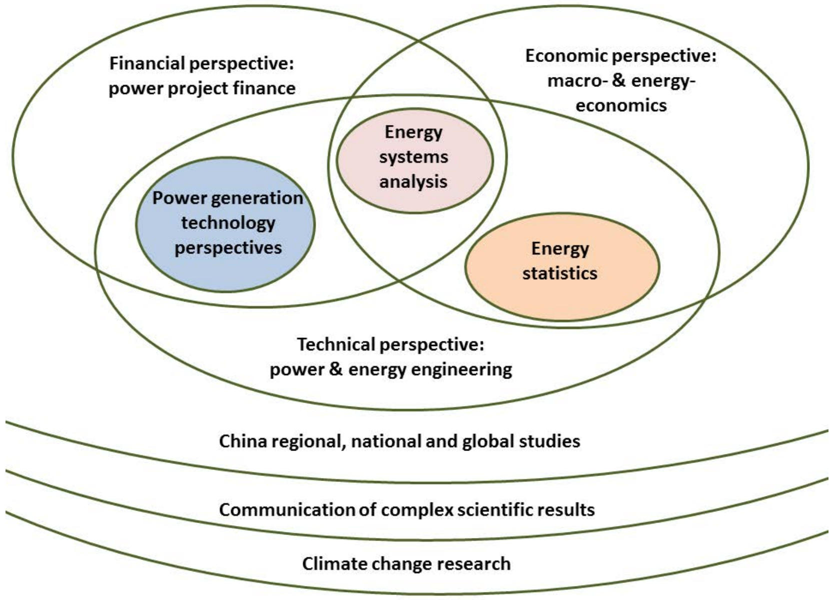
The overall aim of this research is to identify, describe and discuss the main regional characteristics China's "energy revolution". This broad research aim will be approached by means of: (i) measuring and quantifying the current status of China's energy system with a focus on major regional characteristics; (ii) modelling selected, plausible future scenarios for China's regional energy system dynamics, including a few perspectives for renewable power generation technologies and (iii) benchmarking and visualizing associated global impacts of China’s “energy revolution”. In this sense, this research aims to look beyond the daily press headlines on China’s energy and power system developments. Understanding the main characteristics of China's current energy system and exploring plausible future dynamics for the country's socio-economic development, energy supply and consumption patterns, is expected to provide additional insights on the scale, the pace, the domestic challenges and associated global impacts of China's “energy revolution”.

1.4. General framework of investigation: cross-disciplinary & collaborative

The general framework of investigation is a highly cross-disciplinary and collaborative. The theories underlying this research are stemming from the following, mainly quantitative research disciplines: energy and power engineering; macro- and energy-economics; and project finance. Cross-cutting aspects for these three disciplines are China’s energy sector and global aspects, the harmonization of Chinese and international energy statistics, and the scientific communication and visualization of complex research results, such as energy use and CO_2 emission data. In a broader context, the results of this research can feed into a more detailed analysis and discussion of climate change impacts in different regions of China.

While this research and the methodologies used are mainly based in quantitative research, qualitative research aspects played some role in the identification of research topics and required data assumptions for energy models. The core research areas with the various scientific disciplines and indicates the different economic, technical and financial perspectives considered to analyse China’s “energy revolution” are presented in **Figure 3**. An ongoing dialogue with Chinese and international energy researchers was established, maintained and expanded throughout the research. Personal exchanges allowed discussing China-specific statistics, energy technology perspectives and energy scenario assumptions with a broad academic and non-academic audience. On that basis research topics of mutual interest for a new Sino-Danish energy research collaboration could be identified. The development of energy models for China includes some subjective assumptions to cope with lack of data or uncertain data, which are rather qualitative than quantitative. Further details are provided in the methodology sections of the corresponding PhD publications.

Figure 3: Cross-disciplinary scientific disciplines and core research areas.

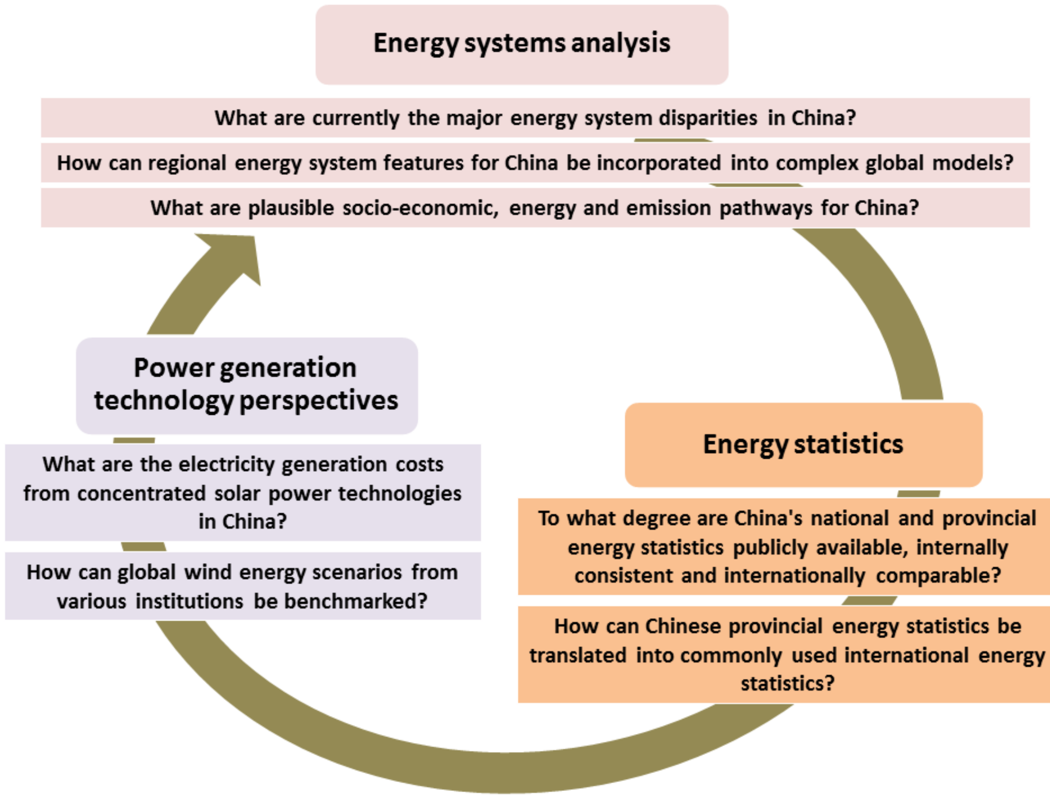


1.5. Research questions

Seven interlinked research questions emerged and were analysed in various collaborations. Figure 4 maps the research questions to the three core research areas, highlighting the cross-disciplinary character of the research areas and the inter-linkages between the research questions:

- **"What are currently the major energy system disparities in China?"**
- **"How can regional energy system features for China be incorporated into global models?"**
- **"What are plausible socio-economic, energy and emission pathways for China and their associated global impacts?"**
- **"To what degree are China's national and provincial energy statistics publicly available, internally consistent and internationally comparable?"**
- **"How can Chinese provincial energy statistics be translated into commonly used international energy statistics?"**
- **"What are the electricity generation costs from concentrated solar power technologies in China?"**
- **"How can global wind energy scenarios from various institutions be benchmarked?"**

Figure 4: Research questions mapped to the core research areas.



1.6. Organisation of the PhD thesis

This PhD thesis is divided into two parts, the PhD synopsis and the PhD appendices. The first part, the PhD synopsis, introduces the research framework and summarises the key research results. This includes a presentation of the research aim and the associated research questions, a discussion of the different methodologies applied, and a visualisation of the linkages between the different independent studies undertaken in various collaborations. A few "Chinese characteristics" are provided throughout the first parts in the form of Chinese proverbs and slogans. The PhD synopsis concludes with a general perspective and recommendations for future research. The second part of the PhD thesis, the PhD appendices, presents the seven main PhD publications[3]. These comprise the following independent studies on different aspects of China's "energy revolution":

[3] There are furthermore two journal articles published open access in Energy Procedia. Due to their short 4 page format required by this journal, these are not discussed in detail as part of the PhD thesis. The corresponding references are available from the overview of PhD publications, see page 9ff.

- **Publication A "China's energy statistics in a global context: A methodology to develop regional energy balances for East, Central and West China"** is a working paper published open access by the Munich University Economic research paper repository in October 2013. It gives a detailed introduction into China's energy statistics and establishes a methodology to develop regional energy balances from China's provincial statistics in the format of a commonly used international energy balance. It has been downloaded about 1000 times and was discussed in Chinese social media in 2013. It is an independent initial study carried out solely by the PhD researcher.
- **Publication B "Modelling tools to evaluate China's future energy system – a review of the Chinese Perspective"** is an invited review article published in Energy in May 2014. It systematically compares and benchmarks 18 energy modelling tools from ten Chinese institutions developed since 2005. It discusses China's future GDP, energy demand and CO_2 emissions from a Chinese perspective, independently from the different modelling approach and institutions. This study was presented at several international energy conferences. It was downloaded 801 times from Elsevier 9 months after its publication and received several citations. It is carried out by the PhD researcher and the Danish PhD supervisor.
- **Publication C "Mapping and benchmarking regional disparities in China's energy supply, transformation, and end-use in 2010"** is a journal article that will be published in Applied Energy in May 2015. It discusses regional disparities in China's current energy flow patterns from a comprehensive, system-wide perspective and highlights challenges between China's national and provincial energy statistics. It is a study carried out by the PhD researcher in collaboration with a Chinese colleague from Tsinghua University.
- **Publication D "Quantifying uncertainty in China's regional energy future towards 2050: a global model soft-linking and comparison exercise"** is an invited journal article that is currently under review by Applied Energy. It represents a first global model comparison with harmonised socio-economic assumptions for China and a first study that down-scales global energy scenarios for three regions of China by applying different top-down, bottom-up and coupled energy planning tools. Initial phases of this study were presented at international energy conferences. It is carried out by the PhD researcher in collaboration with Chinese and Japanese colleagues from China's Energy Research Institute and Japan's National Institute of Environmental Studies (NIES).
- **Publication E "Global energy perspectives with an emphasis on wind energy"** is a peer-reviewed book chapter of an international energy report published in November 2014 by the Technical University of Denmark. It reviews global projections of wind power growth in scenarios from various energy system models, and draws conclusions about the necessary conditions to scale-up wind energy in the future. It is carried out by the PhD researcher in collaboration with the Danish PhD supervisor and Japanese and German colleagues from the International Renewable Energy Agency (IRENA).
- **Publication F "From global modelling to country analysis: focus on China with ETSAP-TIAM and AIM"** is a peer-reviewed book chapter that is currently under review by Springer. It will be published as part of the Springer Research Series "Informing energy and climate policies using energy system models - Economic Impacts of Future Changes in the Energy System" in collaboration with a group of

researchers associated with the International Energy Agency´s Energy Systems Technology Analysis Program (IEA ETSAP). This study presents the soft-linking of a global top-down economic model with a global bottom-up energy system model to establish a common reference scenario. On this basis, global, China national and China sub-regional economic, energy and emission pathways can be documented, analysed, and replicated simultaneously. It is a study carried out by the PhD researcher in collaboration with a Chinese colleague from NIES.

- **Publication G "Electricity generation costs of concentrated solar power technologies in China based on operational plants"** is a journal article that is currently under review by Energy. This study collects data for the first operational concentrated solar power (CSP) plants in China in collaboration with local experts. It calculates and benchmarks the costs of parabolic trough CSP, tower CSP, and dish CSP technologies by applying a levelized cost of electricity model. It is a study carried out by the PhD researcher in collaboration with Chinese colleagues from the Massachusetts Institute of Technology (MIT), Cambridge University and Tsinghua University.

2. Scientific framework and research areas

有的放矢. Shoot the arrow at the target.

毛泽东. Mao Zedong, Chinese president, 1893-1976.

The second chapter of the PhD synopsis introduces the general theoretical framework behind the three core research areas. It furthermore highlights the focus of the research within each research area and introduces key challenges for China-specific research in those areas. References to the corresponding PhD publications are provided, which allow for a more in depth discussion and analysis.

2.1. Energy statistics

A wide range of Chinese national and provincial statistics builds the foundation of this China energy sector-specific research. Provincial and national energy statistics, released by the National and Provincial Bureaus of Statistics (NBS and PBS) of China, allow measuring and modelling the main regional dynamics of China's energy sector. A more detailed background on the history and the current status of China's statistical system is given in the first section of **Publication A – Chinese and IEA energy statistics,** which could serve as a general introduction to China's energy statistics for readers unfamiliar with this topic.

As the quality, reliability, and availability of China's energy data continues to be critically debated in the scientific community, the harmonisation and comparability of Chinese and international energy statistics builds a core research interest. The shortcomings of different official national and provincial data sets released by China's National and Provincial Bureaus of Statistics (NBS and PBS) is a general challenge for reproducible, transparent, timely and internationally comparable China-focussed research. The key data issues for China's energy statistics that are currently discussed in the scientific literature can be summarized as follows: (i) incomplete data coverage, double-counting, and data gaps resulting in inconsistencies between different official statistical data sets [HOLZ, 2014] [ORLIK, 2014] [HAWKINS et al, 2015] [ZHENG et al, 2014], (ii) appearance of manipulated and falsified data, in particular at lower administrative levels [HOLZ, 2014] [GHANEM & ZHANG, 2014] [ORLIK, 2014], and (iii) limited external checks and balances in data reporting and weak international standardisation [HOLZ, 2014] [Ma et al, 2014].

Various researchers therefore apply different and statistical methodologies and tests to examine the quality of China's energy, economic and air pollution data. GHANEM & ZHANG use discontinuity tests and panel matching approaches to test for manipulation in the city level air pollution indices in China from 2001 to 2010. They concluded that about 50% of Chinese cities examined showed signs of manipulation in their reported air pollution levels, for instance due to underreporting [GHANEM & ZHANG, 2014]. HOLZ analysed the quality of China's GDP data extensively in 2014 and failed to detect statistical data irregularities in China's national GDP data. Nevertheless this research highlighted the vast institutional scope of the NBS in potential GDP data falsification, as certain data manipulations would be virtually undetectable [HOLZ, 2014]. In this context, numerous private data providers are emerging, that are offering alternative and client-specific commercial energy data outside the official public statistics [ORLIK, 2014].

Two new pragmatic and transparent statistical methodologies to analyse China's energy data are proposed as part of this research. These aim to advance to debate on the international comparability and internal consistency of China's official and publicly available provincial and national energy balance statistics. **Publication A – Chinese and IEA energy statistics** takes the perspective of an international researcher who is more familiar with commonly used international statistical codes and units of measurement, such as the International Standard Industrial Classification of all economic activities (ISIC) maintained by the UN. **Publication C – Regional energy flow analysis of China** takes the perspective of a Chinese researcher, who is more familiar with Chinese statistical codes and units of measurement, such as the Industrial Classification for National Economic Activities in China (ICNEA). A considerable amount of time was invested to cross-check different inconsistent energy data-sets and to clarify statistical terminology with Chinese and international energy sector experts. Both publications quantify and visualise the main regional energy characteristics of China's current energy system.

2.2. Energy systems analysis

Energy system analysis is a very broad and cross-disciplinary research area that allows measuring the status quo and modelling future perspectives for a country's energy system. In this context an energy system is defined as a complex system that is made up of a series of energy sector specific system components, which are producing, consuming and/or transforming energy. Such energy systems can be expressed as a set of mathematical equations, representing in a simplified form the key characteristics of a real-world system in its current state, and allowing to model potential future energy system scenarios under various policies and constraints. Scenarios are thus a tool helping to discuss, identify, and quantify changes in energy systems. The plausibility of interactions between different system components under various policy constraints can then be analysed. While this research is focussing on China's energy sector and the global energy system, the methodologies used for energy system analysis can be applied to other countries, regions, and cities.

Modern energy system analysis dates back to the global oil crisis in the 1970s and usually links technical energy and power engineering disciplines and energy economic disciplines. International energy institutions, such as Shell and the IEA, have been developing long-term forward looking studies under various oil-price scenarios for many years. Such scenario studies are focussing on plausible storylines on how the future energy markets might develop and how a country or a company could be affected in terms of challenges and opportunities [SHELL 2008], [IEA 2014]. Cost-based optimization methodologies are widely considered as suitable assumptions for constructing and analysing optimal pathways on how a complex energy system might develop.

Optimisation methodologies combined with scenario analysis allow modelling cost-optimal future pathways for energy systems with and without different policies. A number of large-scale and complex global energy models that are based on optimisation frameworks, were developed and applied in many world regions, including China [CHEN et al, 2014], [WANG et al, 2014]. Research that provides energy-sector specific information on the level of China's provinces and regions is currently emerging, as this improves the understanding of China's domestic energy sector dynamics and associated impacts on energy consumption patterns, emissions, future energy sector investments, etc. [YUAN et. al, 2015], [WANG & DUCRET, 2015], [TIAN et al., 2014], [Li et al, 2014], [DONG & LIANG, 2014]. Key challenges and limitations of energy system analysis, and energy scenario analysis carried out with optimization models in particular, include: (i) the establishment of harmonized, plausible future energy system pathways drawing on a variety of statistical data sets and scientific results from different more specialized disciplines; (ii) the access to and use of complex energy system models, their modelling codes and large databases in a competitive research environment; and (iii) the communication and interpretation of results between highly specialized model developers and the broad scientific and non-scientific model user community.

The focus of the research presented here is the analysis of three different regions of China -namely East-, Central- and West-China - in a broader global context. A Chinese perspective on future energy scenarios for China is compiled and discussed in **Publication B – Chinese modelling tools.** This PhD publication provides an introduction to the many Chinese institutions developing and maintaining various energy and power system planning tools in China. China's current energy system and major regional disparities are then quantified in **Publication C – Regional energy flow analysis of China.** Subsequently regional dynamics for China's future energy system towards 2050 are established in **Publication D – Global & China model linking and comparison** and **Publication F – China model coupling.**

2.3. Power generation technology perspectives

Two selected renewable power generation technology perspectives are discussed as part of this research: wind power and concentrated solar power. As this research area is power-sector specific, it could be considered as a sub-topic of an energy system analysis discussed in the previous chapter. The two renewable power generation technologies chosen, wind and concentrated solar power, emerged from mutual research interests identified with different collaborating institutions. Different methodologies and energy modelling tools are used, as the focus of the analysis shifted from a full system analysis to a more specific technology focussed analysis. The focus of **Publication D – Global wind energy perspectives** is to benchmark on-shore and off-shore wind scenarios provided by various institutions relying on various energy modelling tools. The focus of this research is globally while key results for selected countries, including China, are provided. IRENA's recent global renewable energy road mapping exercise that was developed from the bottom-up inputs of various national renewable energy institutions is discussed as a case study for energy scenario analysis. The focus of **Publication G – Concentrated solar power generation costs in China** is to analyse electricity generation costs from the first operational CSP plants in China. Different CSP technology variants and future cost reduction potentials under various assumptions are provided, based on a financial model.

3. Research design, methodologies, and tools

实事求是. Seek Truth from Facts.

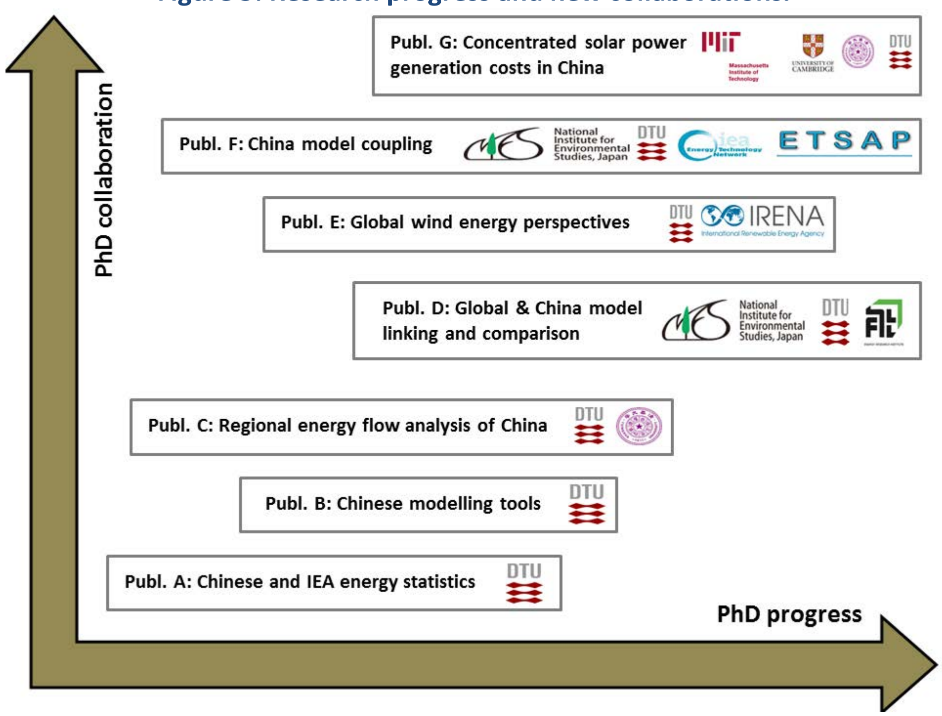
汉书. Han Shu, Han Dynasty, about 36-100 BC, later used by Deng Xiaoping and Mao Zedong.

This chapter of the PhD synopsis gives an overview of the research design, the research progress, and the new research collaborations that were established. It introduces the cross-disciplinary methodologies and tools developed and applied to answer the research questions. It concludes with a critical evaluation of the research design. References to the corresponding PhD publications, where a more in depth discussion and analysis of the research questions takes place, are furthermore provided.

3.1. Overview of the research design

The research areas and corresponding research questions were treated in several studies with different collaboration partners. The main collaboration partners were the University of Cambridge (UK), the Energy Research Institute (China), the National Institute of Environmental Studies (Japan), the International Renewable Energy Agency, the Massachusetts Institute of Technology (USA) and Tsinghua University (China). The research progress over the three year research period from March 2012 to March 2015 and the development of new collaborations is summarized in **Figure 5** below.

Figure 5: Research progress and new collaborations.



Different cross-disciplinary methodologies and tools were applied and developed during the research. The methodologies and tools are linked to the three core research areas in **Figure 6**, while the key PhD publications are matched with the core research areas in **Figure 7**. The circular form of both figures is chosen to highlight the cross-disciplinary connections between the research areas, the research methodologies and the research questions.

Figure 6: Methodologies and tools developed and applied in the core research areas.

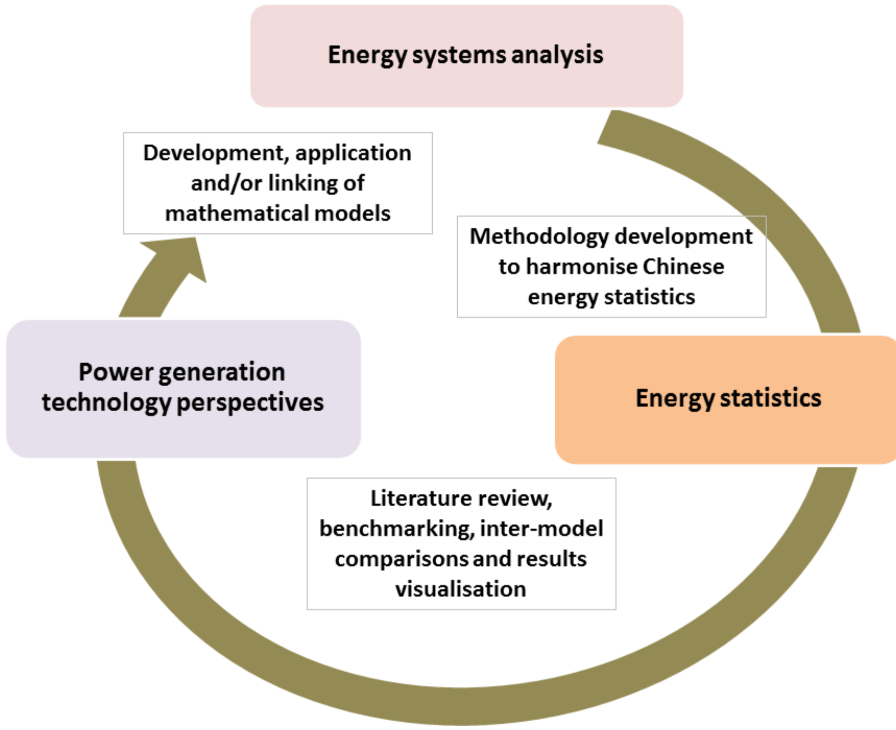
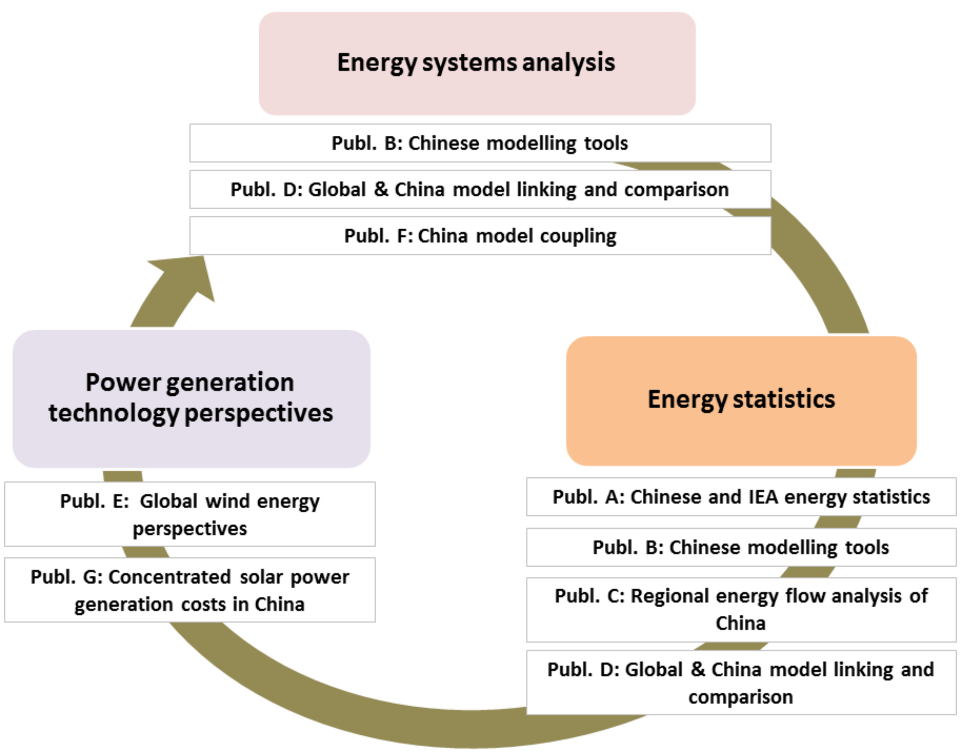


Figure 7: Key publications mapped to the core research areas.



3.2. Development, application and/or linking of mathematical models

Methodologies relating to the development, application and/or linking of mathematical models build a core part of the research. These are required to answer different research questions focusing on China's future energy system in a global context as well as power-sector specific technology perspectives. Suitable energy models to answer the research questions were identified in the beginning of the research. The following key criteria were applied to select such models: (i) the potential to integrate regional energy sector characteristics for China; (ii) the potential to represent both global and regional energy system perspectives for China; (iii) the availability of data and statistics as exogenous model inputs; (iv) the open access to the model, its code and the required computational modeling software; (v) the existence of a global model development and user community; and (vi) the opportunities for collaborations.

Different models were required and applied to answer different research questions. The global IEA-ETSAP TIAM tool was selected to answer several global and China-specific research questions in the energy system analysis research area. A power project-specific financial model was selected and developed from scratch to carry out an analysis of for concentrated solar power plants in China in the power generation technology perspectives research area. Both models are introduced below.

3.2.1. Expansion, application and linking of the global IEA-ETSAP TIAM tool

A common, comparable, and combinable methodology based on the TIMES model framework is chosen to study long-term policy scenarios for China in a global perspective. The MARKAL and TIMES family of models include the TIMES Integrated Assessment Model (TIAM) of the International Energy Agency's Energy Technology Systems Analysis Program (IEA-ETSAP), which is used and expanded in this research. Associated with IEA-ETSAP are energy system analysis groups in nearly 70 countries, among them the Energy System Analysis Group of the Technical University of Denmark. Since about 2005 an extensive documentation for the TIMES model framework and the TIAM tool was started. This documentation consists of several research reports, peer-reviewed journal articles and conference presentation and is made available free of charge under the IEA ETSAP website [IEA-ETSAP, 2015]. The core concepts of the underlying modelling methodology and its computational implementation include: TIMES concepts and theory, a TIMES reference manual and a guide for GAMS implementation [LOULOU et al, 2005] as well as a summary of the mathematical formulation and structure of TIAM [LOULOU & LABRIET, 2007], [LOULOU, 2007].

TIAM can be classified as a global, technology-rich, bottom-up optimisation model in the TIMES framework that is widely used for medium to long-term energy scenario studies. TIAM represents the global energy system, including energy extraction, production, consumption and trade. The world is divided into major energy markets, with China as one of the key emerging energy markets. The reference energy system within a model region is described by the initial capacities of existing technologies, ranging from fossil fuel mining processes, industrial plants, power plants, refineries to vehicles, lighting appliances, and buildings. These capacities will be reduced over the years according to their technical lifetime and replaced by new technologies, considered as new investments. The energy system must comply with a set of technical constraints, such as commodity balances between outputs and inputs for all processes and flow-capacity constraints requiring the necessary available capacity for the flows of commodities. The variables calculated are commodity flows and capacity investment for processes representing new technologies. The core objective function of TIAM minimizes total energy system costs under a set of constraints. Key parameters in the objective function are prices for the most upstream commodities, typically primary fuels, and investment and operating cost of processes. The time horizon of TIAM extends towards 2100, which is needed for long-term climate mitigation policy scenarios. The energy system of TIAM is driven by energy service demand forecasts, provided by global top-down energy-economy models.

As part of this research, the global TIAM tool was reviewed for its representation of China's current energy system, recalibrated with updated China energy balance data, and - as a novel feature - three sub-regions of China were introduced. A global TIAM tool with sub-regional details of China can thus contribute to the energy and climate policy scenario analysis of China's major domestic energy system dynamics and their associated global impacts. TIAM was applied to answer two energy system analysis specific research questions: **"How can regional energy system features for China be incorporated into global models?"** and **"What are plausible socio-economic, energy and emission pathways for China and their associated global impacts?"** The new regional energy demands for China were established by a joint global model soft-linking exercise with the AIM-CGE model developed and maintained by the National Institute of Environmental Studies (NIES) of Japan. Both models were simultaneously expanded with regional China features and harmonised in their baseline assumptions for population growth and economic development scenarios towards 2050. Further details are available from **Publication F - China model coupling**, which documents and tests the common baseline scenario established between both models, and **Publication D - Global & China model linking and comparison,** which takes this global modelling exercise further towards the analysis of a carbon tax scenario and the results comparison with the 23 models from the recent Asia Modelling Exercise (AME) [CALVIN et al, 2012]. A technical description of TIAM with sub-regional China features is available from **Publication D - Global & China model linking and comparison**.

3.2.2. Development and application of a financial model for power project analysis

A technology-specific financial model for concentrated solar power plants in China was developed to provide a few technology-specific power sector perspectives for China. This corresponds to the research question "**What are the electricity generation costs from concentrated solar power technologies in China?"** Levelized Costs of Electricity (LCOE) for different concentrated solar power technology variants in

China were thus calculated. LCOE is the price at which electricity must be generated to break even over the lifetime of a CSP project in China. It can be used as a benchmark to compare different power generation technologies based on their costs of electricity production, as it includes initial investment costs, operation and maintenance costs, cost of fuel, cost of capital, and subsidies (such as tax exemptions). Similar methodologies to calculate and compare renewable power generation costs are applied in IRENA's latest global renewable power generation reports [IRENA, 2015]. This financial model is documented in **Publication G – Concentrated solar power generation costs in China.**

3.3. Methodology development to harmonize Chinese energy statistics

A pragmatic methodology to construct regional energy balances for China in the format of a commonly used international energy balance was developed. As many statistical terms differ between Chinese and international energy statistics, this might result in misunderstandings when communicating of complex scientific research results to different audiences. This suggested methodology aims to advance to discussion about the harmonisation of Chinese provincial energy balances with commonly used international energy balances of China, as the ones developed by the IEA. This new methodology is documented in detail in **Publication A – Chinese and IEA energy statistics.** It is used to answer the following two research questions **"To what degree are China's national and provincial energy statistics publicly available, internally consistent and internationally comparable?"** and **"How can Chinese provincial energy statistics be translated into commonly used international energy statistics?"**

This new methodology was used to calibrate the new regional China features in the global TIAM tool and allowed to construct internationally comparable regional energy scenarios for China. The main advantage of this methodology is that it allows to model internally consistent and internationally comparable regional energy scenarios for China. On this basis, a modelling exercise on future regional perspectives for China's domestic energy system in a global context was carried out with TIAM. This methodology documents in a transparent way the qualitative expert assumptions required when there is a lack of comparable, official Chinese energy data available. **Publication D - Global & China model linking and comparison** and **Publication F - China model coupling** provide further details on the application of this methodology.

Another methodology was developed to constructed and benchmarked national and regional energy flow diagrams for China within the area of Chinese energy statistics. This methodology is applied to calculate regional energy flows from China's aggregated provincial statistics, and highlights expert assumptions, such as fuel conversion factors, in a transparent way. Major regional energy flows for coal, oil, natural gas, electricity and renewables were visualised in energy flow diagrams and associated data issues were highlighted. This work is carried out to answer the research question **"What are currently the major energy system disparities in China?"** It is documented in detail in **Publication C - Regional energy flow analysis of China.** This work remains within the area of Chinese energy statistics, as Chinese energy terminologies and non-standardised units of coal-equivalents are taken into account. This statistical methodology aims to improve the communication of China-specific scientific results to a broad audience, mainly targeting international researchers unfamiliar with Chinese energy statistics.

3.4. Literature review, benchmarking, and inter-model comparisons

China-specific energy research, as the one carried out here, is expected to benefit from more comparative analysis. Applying various comparative methodologies and tools is expected to increase the understanding of China's "energy revolution" from various perspectives and allow for various research collaborations. In this context literature reviews, China-specific and global benchmarking exercises and collaborative inter-model comparisons were integrated. Whenever possible, these comparative methodologies were integrated in the research design of different studies and their results were visualised for a broad academic and non-academic audience. **Publication D – Global wind energy perspectives** benchmarks and compares future perspectives for wind energy generation from seven different leading institutions using different global energy system planning tools. It is answering the research question **"How can global wind energy scenarios from various institutions be benchmarked?"** A comparison of energy scenarios computed by two complex global modelling tools with regional China features is part of **Publication D - Global & China model linking and comparison** and **Publication F - China model coupling.** A Chinese perspective on China's future energy sector development was established in **Publication B – Chinese energy models**. This study reviews and compares the state-of-the art of energy modelling tools developed by Chinese institutions since 2005. These three different studies all contribute to the discussion of plausible future energy system pathways for China, providing answers to the research question **"What are plausible socio-economic, energy and emission pathways for China?"**

3.5. Critical assessment of the research design

As with any new and challenging intercultural and cross-disciplinary research, some aspects of the research design proved challenging and several measures were taken to cope with those. Challenges included a new Sino-Danish collaboration framework, the complexity of global energy models needed for China-specific scenario analysis, the lack of harmonisation between Chinese and international energy statistics, and the fast-pace and highly competitive research environment for China-specific energy sector studies.

Research periods were split between Denmark and China to efficiently progress within a limited three year time frame. While computations were mainly carried out in Denmark, the four different research stays in China were highly useful to collect, to cross-check and to discuss energy data for China. This was crucial to establish new collaborations and to receive a continuous feedback from various Chinese energy sector colleagues on how to best approach the different research questions.

Some of the energy system analysis specific research questions were considered as very open and flexible in the beginning of the research. This was expected to allow for collaborations that are based on mutual interests, rather than defining a highly detailed research plan in the beginning. As this research was carried out as part of a new bilateral Sino-Danish collaboration framework, new partnerships needed to be established and maintained, which required time, patience, and mutual trust in order to overcome cultural and language barriers.

A strategic choice towards exploring interesting research questions in-between scientific disciplines was made rather than specialising over time in a single research area, methodology or tool. China-specific energy system research is continuously challenged to be up to date, consistent, and relevant for both the interests of international researchers and Chinese researchers. To cope with these challenges, different perspectives were taken, different modelling tools were used, and different collaborations established. New cross-disciplinary research questions of interests for Chinese and international energy researchers emerged in this context. This strategic choice acknowledges the inherent uncertainty of future energy scenarios for China and the current challenges in harmonizing Chinese and international energy data. As no modelling exercise and no modelling tool is without limitations, and the use of models in this research should be seen in the perspective of starting a discussion on China’s current and future energy sector developments. A considerable effort was made on documenting required assumptions in a transparent way.

4. Key results summarised: Answering the research questions

我坚信，到中国共产党成立１００年时全面建成小康社会的目标一定能实现，到新中国成立１００年时建成富强民主文明和谐的社会主义现代化国家的目标一定能实现，中华民族伟大复兴的梦想一定能实现. Achieving the “Two 100s”: the material goal of China becoming a “moderately well-off society” by about 2020, the 100th anniversary of the Chinese Communist Party, and the modernization goal of China, becoming a fully developed nation by about 2049, the 100th anniversary of the People’s Republic.

习近平. Xi Jinping, current Chinese president, China dream speech, November 2012.

This chapter of the PhD synopses summarises the key results of the research by answering the seven inter-linked research questions in the three cross-disciplinary research areas “energy statistics”, “energy systems analysis” and “power generation technology perspectives” (see **Figure 4**). For easy reference, the research highlights of the different stand-alone PhD publications are summarised in **Figure 8**. It is suggested to read the corresponding publication(s) for each research question, as this will allow for a deeper understanding of the context, methodologies, results and limitations behind each study.

Figure 8: Research highlights from the different publications.

Publ. A: Chinese and IEA energy statistics
- an overview of the development of China's statistical system
- a discussion of the reliability, accuracy, and availability of energy data for China
- a comparison of Chinese energy statistics and IEA energy statistics
- a pragmatic methodology development to current analyse regional energy trends in China

Publ. D: Global & China model linking and comparison
- a coupling of two complex top-down and bottom-up energy planning tools with sub-regional detail on China
- an international model harmonization, benchmarking, and results comparison exercise
- a regional analysis on China's future energy system in a global perspective
- a discussion of data ranges in China's future energy and emission scenarios

Publ. B: Chinese modelling tools
- a China-specific model review
- an analysis of the Chinese perspective towards a low carbon economy
- a summary of energy planning and modelling tools in China
- an inter-model results comparison and benchmarking exercise

Publ. E: Global wind energy perspectives
- an overview of the most recent wind power investments at a global scale
- a comparison of future global wind power projections from 7 leading international institutions
- a summary of the role of wind power in IRENA's a global renewable energy road map towards 2030

Publ. C: Regional energy flow analysis of China
- an energy system wide mapping of regional and national energy flows in China
- a discussion of regional energy system disparities
- a visualization of China's energy balance with Sankey diagrams

Publ. F: China model coupling
- a discussing of baseline scenario assumptions for sub-national energy system dynamics for East-, Central and West-China until 2050
- a comparison of China-regional and global energy and emission results from three different models (top-down, bottom-up, coupled)

Publ. G: Concentrated solar power generation costs in China
- a study that analyzes three different concentrated solar power (CSP) technology variants in China
- a first national CSP database for China, consisting of seven CSP plants under construction and operation
- a calculation of the range of levelized costs of electricity for operational CSP plants in China
- a discussion of scenarios for future CSP cost reductions in China

4.1. Energy statistics - To what degree are China's national and provincial energy statistics publicly available, internally consistent and internationally comparable?

The research question **"To what degree are China's national and provincial energy statistics publicly available, internally consistent and internationally comparable?"** builds the statistical foundation of this research and is addressed in two publications. Major challenges of China's statistical system are reviewed in their historic context and summarized in **Publication A - Chinese and IEA energy statistics.** This publication also indicates current challenges in comparing and harmonising Chinese and commonly used international energy statistics. **Publication C - Regional energy flow analysis of China** answers mainly the research question **“What are currently the major energy system disparities in China?”** and includes a detailed discussion of data challenges and inconsistencies of Chinese energy statistics for the example of the year 2010.

China's statistical system is in a continuous transition and modernisation phase. As an emerging economy, the country has a statistical system that is continuously adjusting as its economy and policies develop. Incomplete energy market reforms and the persistence of some structural features from the soviet style planning system remain present in current Chinese statistics. The growth of the economy, the extensions in the statistical coverage of sectors of economic activity previously omitted, and the introduction of new statistical methods have led to a rapid increase in the size of the statistical system. Statistics developed during the planning economy are planned to be cut off by while new and improved statistics on resources, environment, and the service sector will be introduced. Official bottom-up reported statistics are partly incomplete and difficult to verify with a top-down approach. China’s annual statistics are intended to cover all economic activity, but NBS has better access to information from bottom up reporting in some end use sectors than in others.

Since the 1990s the portion of economic activity within the control of government has shrunk, and with it the ability to gather data, gradually eroding the completeness and accuracy of bottom up statistics. For end-use sectors dominated by a few, large state-owned entities, like the iron and steel industry, reliable bottom up statistics on consumption are available. In other sectors, however, there is only a thin statistical basis for gathering energy consumption statistics, as limited detailed national surveys are available. This is especially a challenges in economic sectors in which non-state enterprises are more numerous or changing frequently. Expert estimates are required for instance for energy consumption of many small locally owned/controlled power plants, refineries, mines and other installations at lowest administrative levels and renewable rural energy use.

Since the development of China's energy statistical system in the 1980s, the amount and variety of statistical materials about China‘s energy system continues to increase. China's statistical material published to date is vast, covering for example more than 50 annual statistical yearbooks for 2012. Each statistical yearbook usually includes at least 400 pages in its printed edition. As most statistics in China are not considered to be public goods, the purchasing prices for statistical yearbooks vary over a wide range. The number of Chinese and international data providers is also increasing. Many industry associations, including the China Building Materials Industrial Association, the China Automotive Industry Association and the China Nonferrous Metals Industry Association, and other high level government institutions, such as the National Development and Reform Commission and the new China National Renewable Energy Centre, are publishing energy related statistical yearbooks in parallel to the official statistics of the NBS. Increased competition among governmental and private data providers can result in the publication of very similar statistical yearbooks for a sector.

One PhD publication takes a more detailed look at recent energy data for China in 2010, from both the perspective of national and provincial energy statistics. Major data differences between the official national and provincial energy balances of China for the year 2010 were highlighted in **Publication C -**

Regional energy flow analysis of China, in particular for coal. Positive data differences between national and aggregated provincial statistics were detected for thirteen of the identified fourteen major fuel-specific energy flows in China’s energy balance. That means that in general the aggregated provincial energy indicators are higher than the corresponding national indicator. The only exception to this phenomenon is the international net import of oil/petroleum products in 2010, where the aggregated regional energy indicators are lower than the corresponding national indicator. When ranking the fuel flows according to their size of relative data-difference, the highest uncertainties relate to direct coal use in industry (+46%); international net imports of oil/petroleum products (-32%); coal in total primary energy supply (+22%) and secondary product use in industry (+22%). Most of the fuel-specific energy flows with larger data difference relate to coal and secondary products. In comparison, data differences in electricity flows are rather small. This indicates that in particular all coal-related energy indicators, in all section of China's 2010 energy balance, need to be taken with sufficient caution, while official electricity data are more reliable.

In summary, Chinese energy statistics can serve as a starting point for energy system analysis in general and power sector analysis in particular, when these are treated with sufficient caution. While the public availability of national and provincial energy data for China keeps increasing, their internal consistency and internationally comparability needs additional assumptions and methodologies. Often expert judgements are required to fill data gaps. In particular official coal statistics, the key statistics required for measuring and modelling China’s energy system, are challenging to deal with. Official electricity statistics are more reliable, as these can be measured more accurately.

4.2. Energy Statistics - How can Chinese provincial energy statistics be translated into commonly used international energy statistics?

An international researcher’s perspective is taken to “bridge the gap” and “translate” between Chinese statistics and international statistics. The corresponding research question **“How can Chinese provincial energy statistics be translated into commonly used international energy statistics?”** is addressed in **Publication A - Chinese and IEA energy statistics**. The methodology section of this working paper includes a pragmatic approach to transform regional energy balances for China - rooted in Chinese statistical definitions and Chinese energy units - into commonly used international energy statistics – rooted in standardized international energy units, as used by the International Energy Agency (IEA). This methodology is later applied develop and calibrate regional energy system feature of China in the global IEA-ETSAP TIAM model. On this basis a novel and regionally detailed scenario analysis of China in a global context is carried out.

The new and pragmatic statistical triangulation methodology developed consists of the following five steps:

- Step 1: Use the national IEA energy balance of China as a starting point for international analysis.

  The IEA energy balance is serving as a benchmark and ensures international comparison of statistical categories and SI units. IEA's national energy balances for about 100 non-OECD countries, including China, are published annually in September. IEA's energy balance format distinguishes primary energy supply, energy transformation, energy industry own use and final energy use for up to 60 fuels and energy commodities. For China, the IEA energy balance will include fuel re-allocations in different sectors to improve the international comparability of statistics.

- Step 2: Match the energy indicators of China's provincial energy balance with the corresponding ones in the IEA national energy balance.

  China's national and provincial energy balance tables are published by NBS usually in September, one year after the primary energy statistics are released. China's national energy balance includes primary energy supply, in- and outputs of fuels in transformation processes, losses, and final energy consumption. In total 32 fuels and energy commodities are covered by NBS, it is thus less detailed than the IEA energy balance. Most energy indicators of China's provincial energy balance can be matched with corresponding energy indicators in the IEA national energy balance of China.

- Step 3: Identify regions in China with different energy system characteristics to build bottom-up energy balances from provincial energy data.

  The suggested regional definition of China applied in this study is based on the Seventh Five-Year Plan (1986–1990), which grouped all provincial level divisions of China into three economic zones in order to promote a medium to long term economic development, specialization, and division of labour. This is a frequent regional division of China for the purpose of a general energy system analysis.

- Step 4: Calibrate the national benchmark from IEA with regional energy shares from NBS

  After regional shares for East, Central and West China are derived from provincial energy statistics and corresponding national energy indicators in the IEA energy balance have been identified, regional shares can be calibrated against an internationally comparable national benchmark of China. In this methodology, the IEA China energy balance is used as a national benchmark.

- Step 5: Use closely related statistics and expert assumptions to check consistency.

  Expert assumptions and cross-checks allow to further minimizing uncertainty and inconsistencies in the established regional energy balances in IEA format. For consistency checks, the fuel consumption in a given sector could be compared to output and energy intensities that are reported in alternative Chinese statistics, such as industry yearbooks.

4.3. Energy Systems Analysis - How can regional energy system features for China be incorporated into complex global models?

New methodologies are needed to integrate regional features of China's energy sector into global models. Such a methodology is suggested in Chapter 4.2 above and documented in detail in **Publ. A - Chinese and IEA energy statistics.** Limitations of this methodology are due to the lack of harmonisation between Chinese and international energy statistics. The harmonisation of final energy consumption data is especially challenging, in particular in industry. Chinese industrial statistics are often more aggregated and follow a different code of classification of economic activities, than international energy statistics. This results in the need for additional, alternative datasets and expert assumptions. Current statistical challenges are discussed in detail and required assumptions are documented for a wide range of energy balance indicators in **Publ. A - Chinese and IEA energy statistics**.

This new methodology was successfully implemented in a global energy system model, namely the IEA-ETSAP TIAM model. It was subsequently used to develop internationally comparable and internally consistent regional energy scenario analysis for China. It can be concluded that this transparent methodology can serve as a basis to translate between different statistical systems, before these are better harmonised and integrated. As it relies on the internationally commonly used, internally consistent and internationally comparable benchmark of the IEA, the harmonisation of regional energy characteristics of China is ensured. It thus answers the research question **"How can regional energy system features for China be incorporated into complex global models?"**

4.4. Energy Systems Analysis - What are currently the major energy system disparities in China?

A methodology was established to identify major regional energy system features of China's current energy system and quantify major regional disparities. The corresponding research question **"What are currently the major energy system disparities in China"** is addressed in **Publication C - Regional energy flow analysis of China.** It is part of the research area "Energy System Analysis". China is disaggregated in three commonly used economic regions for this purpose: East-, Central-, and West-China, in line with the current regional definition of the National Energy Administration (NEA) of China. These regions represent aggregations of Chinese provincial units. **Publication C - Regional energy flow analysis of China** includes several figures to visualize major regional disparities and associated data challenges.

Major energy supply disparities in China for the year 2010 highlight the dependence of East-China's coal supply on net-domestic imports from Central- and West-China. Coal is the major fuel in China's national primary energy supply. West-China accounts for about 50%, Central-China accounts for about 39% and East-China accounts for about 11% of the national domestic coal production. Total primary energy supply of oil/petroleum products is dominated by East-China, which accounts for about 65% in the corresponding national total. East-China is also a major net-exporter of oil and petroleum products to other regions of China. Natural gas/LNG production and primary electricity from renewable and low-carbon energy sources (hydro, wind, solar, nuclear) are of minor importance, at both the national and sub-national level.

Major disparities in China's energy transformation in 2010 indicate the dominance of East-China in coal-based power generation and oil refining. Power production from coal is the largest energy transformation process in 2010, both at a national level and in all regions of China. West-China accounts for about 31%, Central-China for about 36%, and East-China for about 51% in the national coal input for all energy transformation processes. Coking takes mainly place in Central-China (about 40%) and in East-China (about 35%). These two regions produced most of the national coke output in 2010. Coal fired power generation can be mainly mapped to East-China (about 50% of the national total). Accordingly most of the coal inputs to thermal power plants are also mapped to East-China. Refining took mainly place in East-China in 2010, where about 90% of inputs for refineries can be traced.

East-China also dominates China's final energy use in 2010, in particular industrial energy consumption. About 49% of the total national energy use in industry can be mapped to East-China. Coal, electricity and oil/petroleum consumption in industry are highest in East-China, accounting for about 58% of the national coal use, 53% of national electricity use and about 70% of national oil/petroleum product use in industry. About 55% of China's petroleum products consumption in the residential sector and about 65% of China's petroleum products consumption in the transport sector can be mapped to East-China.

4.5. Energy Systems Analysis - What are plausible socio-economic, energy and emission pathways for China?

The research question "What are plausible socio-economic, energy and emission pathways for China?" is a very broad research question and thus addressed in several publications using different methodological approaches and different collaborations. A state-of-the-art review of the Chinese perspective on the country's socio-economic, energy and emission pathways is given in **Publication B – Chinese modelling tools.** A new perspective to answer this research question is provided in **Publication D - Global & China model linking and comparison** and **Publication F - China model coupling**. These two publications are a collaborative effort between the Technical University of Denmark, the National Institute of Environmental Studies (NIES) of Japan and the Energy Research Institute (ERI) of China. These publications document the development, application, and linking of two complex global energy-economy models with regional China features. On this basis, a global and regional China-specific scenario analysis under harmonised assumptions is performed.

Publication B – Chinese modelling tools reviews the state of the art of Chinese energy modelling from recent English language publications between 2005 and 2013. The review did not only include academic literature, it also comprised project reports from international and bilateral energy collaboration projects and policy briefs and magazines released by public sector energy institutions and think tanks, such as China's Energy Research Institute. In general, access to the tools and the complete set of calculation results remained challenging, as many relevant China energy sector studies are carried out outside academia. Nevertheless, 18 different energy modelling tools were identified, described and compared in their underlying reference scenarios and default assumptions.

This review of Chinese energy modelling tools and energy policy recommendations concludes that the Chinese perspective, independently from the modelling approach and institution, suggests a rather gradual and long-term transition towards a low carbon economy in China. Few reference scenarios include an emission peak or stabilisation period before 2040. While policy scenarios frequently suggest efficiency improvements, a short-term and large-scale introduction of new energy system technologies, such as non-fossil power generation technologies, is rarely recommended. Potential global impacts of China's future energy system are hardly analysed by Chinese researchers. One reason might be that no global energy modelling tool is currently used and maintained by a Chinese institution. When comparing and benchmarking the results for three main energy system indicators across 18 Chinese energy models, considerable result ranges in the reference scenarios are reported: (i) China's GDP is projected to grow by 630-840% from 2010-2050, (ii) China's energy demand is projected to increase by 200-300% from 2010-2050, and (iii) China's associated CO_2 emissions are projected to rise by 160-250% from 2010-2050.

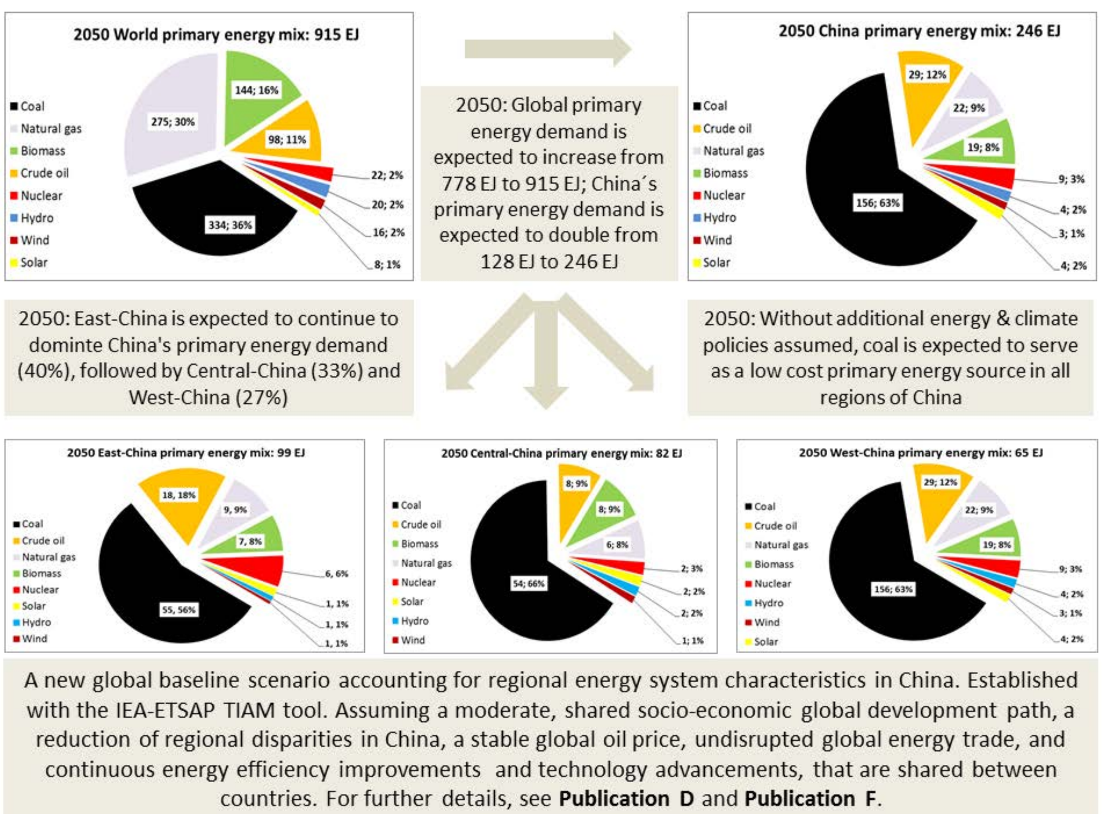
Publication D - Global & China model linking and comparison and Publication F - China model coupling provide new regional insights for future socio-economic, energy and emission pathways for China and associated global impacts. This complex research required enhanced global energy modelling tools for China, as current global models do not include dedicated sub-regional energy system features for China in a coherent global modelling framework. The bottom-up IEA-ETSAP TIAM tool and the top-down AIM-CGE tool were expanded and subsequently soft-linked with regional China features in order to study socio-economic, energy and emission pathways for East-, Central- and West-China towards 2050. The baseline scenario follows the GDP and demographic trends of a newly developed, moderate Shared Socio-economic Pathways (SSP2) scenario [O’NEILL et al., 2013]. The SSP2 pathway is downscaled for China, following China’s regional development principle that the existing socio-economic disparities within China will be narrowed towards 2050. Both models stand-alone and soft-linked compute consistent socio-economic, energy and emission pathways for China at a national level and a regional level. Main characteristics of the pathways are independent from the modelling tool used, thus seem plausible and in line with the modelling assumptions.

Publication D - Global & China model linking and comparison showed that sub-regional China features, when incorporated into complex global models, fall well within the range of China-specific modelling results presented in the scientific literature, and can provide additional regional details for China’s domestic energy system dynamics. As the data ranges for China’s future energy consumption and CO_2

emissions in the literature are rather high, benchmarking results with previous international scenario studies, such as those of the Asia Modelling Exercise (AME) [CALVIN et al, 203], is useful to continue to discuss modelling assumptions and potential policy impacts.

Without additional energy and climate policy assumed beyond the baseline assumptions, such as an economy wide carbon tax, coal is expected to remain the dominant, least-cost primary energy source in East-, Central-, and West-China towards 2050. This baseline scenario, which was jointly developed with NIES and ERI, includes assumptions about the future global economic development, population growth, stable energy markets and international energy trade, and continuous technological advancements and efficiency improvements. Future global and regional energy scenarios for China towards 2050 were modelled with the IEA-ETSAP TIAM tool with new regional China features. **Figure 9** below gives a snapshot on primary energy demand globally, in China and in regions of China, which allows for a comparison with **Figure 1**. While the global primary energy mix under the baseline scenario is expected to rely much less on coal than today (about 36%), coal is expected to remain the major primary energy source in China (about 63%). East-China is expected to be the region with the lowest coal share in primary energy, about 56%. This indicates the challenges China is facing to advance towards a low-carbon development in the next few decades. A more detailed discussion of this joint scenario exercise, that also included a carbon tax scenario, is provided in **Publication D - Global & China model linking and comparison.**

Figure 9: Future primary energy mix modelled in IEA-ETSAP TIAM: Baseline assumptions and results for East-, Central-, and West-China in 2050



Publication F - China model coupling highlights that China-specific modelling exercises should be sufficiently harmonised and documented first, before applying regionally detailed modelling framework to study policy scenarios for China in a global context. Differences in quantitative modelling results for China can be mainly explained by different technology representation and different statistical inputs in both models.

4.6. Power generation technology perspectives - What are the electricity generation costs from concentrated solar power technologies in China?

A study was carried out to analyse and benchmark the costs of three concentrated solar power (CSP) technology variants in China: parabolic trough CSP, tower CSP, and dish CSP. Different from previous China-specific analysis that base on many assumptions and the data from other countries, this study assesses the economic feasibility of three CSP technology variants in China based on operational plants. Data for CSP power plants were obtained mostly from interviews in China, as official statistics do not provide sufficient level of detail for such an analysis. A financial model for power project analysis was developed and used. The technology-specific research question **"What are the electricity generation costs from concentrated solar power technologies in China?"** is answered in **Publication F - Concentrated solar power generation costs in China**. It represents a new collaboration between MIT, University of Cambridge, the Technical University of Denmark and Tsinghua University.

The current levelized cost of electricity of CSP plants in China were calculated in range of 1.2-2.7 RMB/kWh (0.19-0.43 US$/kWh) and tower CSP was identified as the most promising CSP technology variant for China. A sensitivity analysis on future LCOE for CSP in China was furthermore carried out, introducing amongst others further assumptions on cost reductions in the developed model. This indicated that tower CSP would be the best short-term CSP technology with the lowest LCOE of 0.87 RMB/kWh (0.14 US$/kWh). In the longer term tower CSP with mature thermal storage systems could achieve a LCOE decrease of up to 0.47 RMB/kWh (0.08 US$/kWh). This holds under the conditions that the total investment costs would be managed well, that CSP technologies installed in China would be in line with the globally best available CSP technologies, and that China continues a favourable set of CSP investment conditions and regulations. Based on expert interviews carried out on-site in China, tower CSP might also be the most advantageous CSP technology for China as a high share of local content manufacturing could be achieved.

4.7. Power generation technology perspectives - How can wind energy scenarios from various institutions be benchmarked?

Another study was carried out to compare various ambitious long-term green-house gas reduction scenarios with regards to the potential role of wind power in the future global power system. A benchmarking exercise based on the published wind power studies from various modelling tools was carried out in this context. The technology-specific research question **"How can wind energy scenarios from various institutions be benchmarked?"** is thus addressed in **Publication E - Global wind energy perspectives**. In collaboration with the International Renewable Energy Agency (IRENA), global energy system models from leading energy industry, research and international organisations were reviewed and benchmarked. These institutions comprised International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), the International Institute of Applied Systems Analysis (IIASA), the Global Wind Energy Council (GWEC), Exxon Mobile and the US Department of Energy (US DoE).

The key assumptions behind the different studies were reviewed and the share of wind power in the future generation mix was selected as a key indicator to benchmark the different studies. Scenario results for wind power published in studies from these different institutions can be compared and ranked, as all studies include results for future electricity generation in general and wind electricity generation in particular. Differences between computed scenario results, in this case different ranges for wind power in the energy mix, can be explained by different underlying assumptions and different modelling frameworks used. Visualising result ranges of a set of scenarios together with key modelling assumption provided useful to present complex scientific results for a broad audience. See **Publication E - Global wind energy perspectives** for further details.

The following main results were obtained from this wind power benchmarking exercise:

- The main assumptions and modelling frameworks behind these scenarios differ considerably. The various projections for wind power towards 2050 show a wide range: from a conservative 2500 TWh/y to an optimistic 14000 TWh/y;
- The most progressive global wind power projections were published by Greenpeace, the Global Wind Energy Council and IRENA while the most conservative global wind power projections were presented by Exxon Mobile and the US Department of Energy;
- Taking the IRENA global renewable energy roadmap towards 2030 and its database as an example, the countries with the largest expected share of wind power in 2030 are Denmark (with over 60% of its electricity from wind), followed by Germany and the UK (40–50% of electricity from wind). Australia, France and the US (20% of electricity from wind) come next, and then a group that includes China (15–20% of electricity from wind).

5. General conclusions, policy implications and outlook

知之为知之，不知为不知，是知也. If you know, recognize that you know; if you don't know, then realize that you don't know: That is knowledge.

孔子. Confucius, Chinese philosopher, 551–479 BC.

This chapter of the PhD synopsis takes a general perspective on the results obtained and draws conclusions with regards to policy implications, general limitations and future avenues of research. It furthermore summarizes the time-horizon and the geographic boundaries of the research from the different studies. Some initial scientific metrics and public outreach figures are also given.

5.1. General conclusions & policy implications

The results of this thesis are relevant for a broad scientific and public audience interested in China's ongoing energy and power system transition. The collaborative and cross-disciplinary approach of this research allows gaining a deeper understanding of China's "energy revolution" from various economic, technical and financial perspectives, while highlighting associated complexities and uncertainties, such as data challenges. This broad research topic was approached from different global, China-national, and China-regional perspectives, as summarised in **Figure 10,** and considered both short-term and long-term time horizons, as summarised in **Figure 11**. It combines technical, economic and financial perspectives to analyse several inter-linked research questions for China's energy and power sector, based on various new collaborations established. Novel scientific approaches and results of this research include: (i) a pragmatic methodology development to construct sub-national (regional) energy balances for China in the format of a commonly used international energy balance; (ii) a review and benchmarking exercise of 18 Chinese energy modelling tools followed by a discussion of the Chinese perspective towards a low carbon economy; (iii) an energy system wide mapping of regional energy flows in China to describe current regional energy system disparities; (iv) a coupling of two complex top-down and bottom-up global energy planning tools to model future regional dynamics of China's energy sector in a global perspective; and (v) a calculation of electricity generation costs of concentrated solar power plants in China and a discussion of future technology perspectives.

Figure 10: Geographic boundaries of the research.

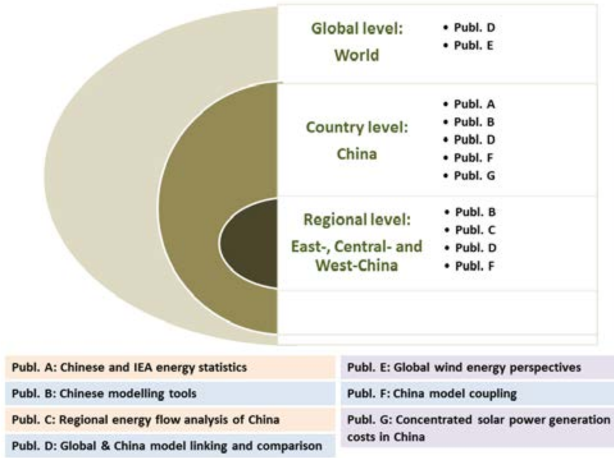
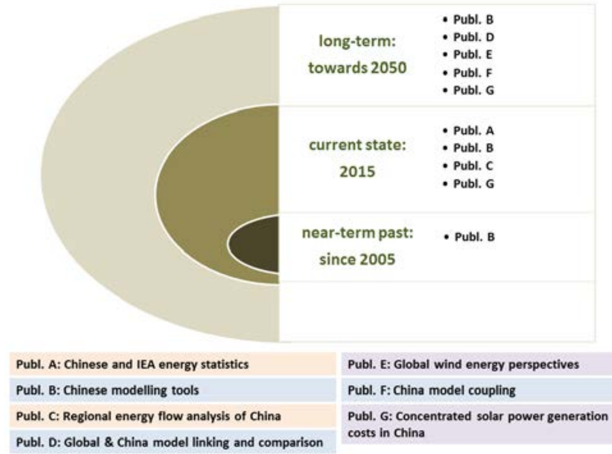


Figure 11: Time horizon of the research.



This research contributed to a better understanding of China's domestic energy statistics, in particular for international researchers unfamiliar with the current status of China's statistical system. This research thus helps to build a more solid foundation for internationally comparable energy research at the level of China's regions and provinces. By proposing new methodologies for "translating" between the worlds of Chinese and international energy statistics, this research is expected to serve as a background to a range of more detailed China-specific and global energy and power sector studies. Inconsistencies in different statistical datasets for China will likely persist in the future and can only be solved by an advancement of statistical reforms within China. New research in this field should therefore clearly highlight data challenges and attempt to assess those impacts on the results, in particular when evaluating policies. Official coal-related statistics, that are crucial for measuring China's currently coal-dominated energy system, should be carefully analysed and cross-checked with Chinese energy experts and alternative data sets. Visualisation of such data issues is considered as helpful to advance the debate on the statistical developments in China, the international harmonisation of energy statistics.

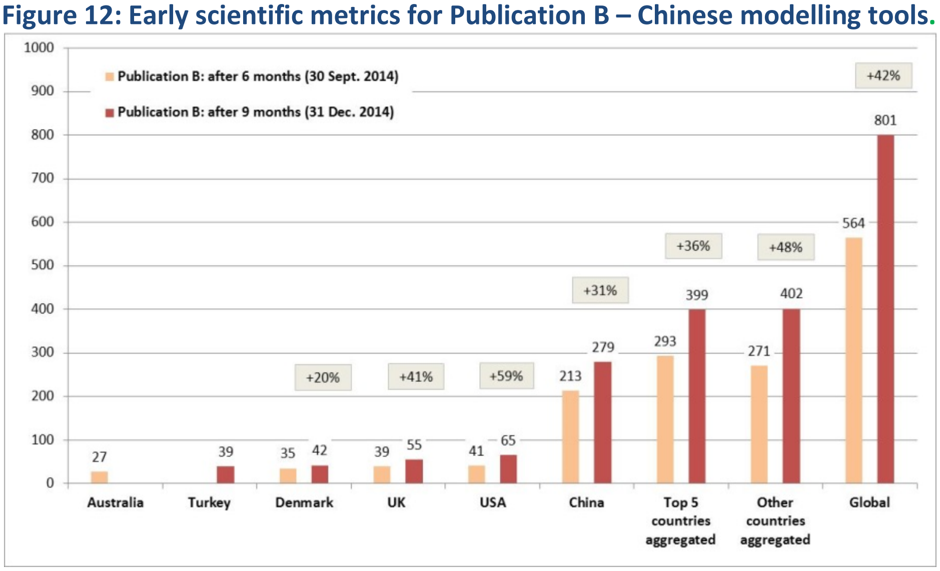
Comparative energy and power sector analysis for China, relying on different energy system models and methodologies, as carried out here, helps to understand the various challenges for China's energy transition and its associated global impacts. Modelling plausible socio-economic, energy and emission scenarios for different regions in China, in close collaboration with Chinese researchers, was another main interest of this research. Developing a global technology-rich energy system model with sub-regional China features and linking it to a global economic model provided new insights on how different regions of China might develop and what global energy consumption requirements and CO_2 emissions might result. Energy system analysis of China will benefit from more harmonised and comparative frameworks that integrate global, national and regional perspective for China. Such new framework was suggested, tested, and applied in this research in order to study a baseline scenario towards 2050 and a moderate carbon tax policy scenario. Future work could be based on these results and could for instance analyse the regional impacts of China's various national energy and climate policies. Benchmarking of scenario results and visualisation of comparable results from different modelling tools was a focus of this research. This aims to make China-specific scenario results and associated uncertainties easier to understand and to discuss with a broad scientific and public audience, including policy makers.

Renewable energies are emerging in China and provide for new and interesting research topics, while much uncertainty remains about their future role in China's currently coal dominated energy system. Calculating electricity generation costs for the first operational CSP power plants in China provides new insights on the current status and future perspectives for a specific emerging renewable energy technology in China. A more detailed technology-specific analysis can in turn contribute to improve the technology-specific details in power and energy system models for China. Other emerging renewable energy technologies and clean coal technologies in China could be analysed with similar methodologies and tools.

5.2. Scientific metrics

This research contributed to the creation of China energy system knowledge via the publication of scientific journal articles and peer-reviewed book chapters. The book chapters were explicitly intended for a broad audience and might serve as teaching materials. The first journal article of this PhD research, **Publication B – Chinese modelling tools**, was published in April 2014 and received five citations as of March 2015. The download metrics of this publication from Elsevier indicate a very broad, global interest in this work. The top countries in the publication download statistics, as shown in **Figure 12** below, included China, USA, UK, Denmark, Turkey and Australia. The "Chinese perspective" of this research approach, which focused on Chinese institutions, Chinese researchers and Chinese modelling tools, could be considered again in future China-specific energy research.

Figure 12: Early scientific metrics for Publication B – Chinese modelling tools.



The improved modelling of China's energy system contributed to the update of the global IEA-ETSAP TIAM tool. This PhD research is part of the Danish contribution to the IEA-ETSAP Annexe XII "Policy Analysis Tools for Global Sustainability: E4 systems tools and joint studies" running from 2011-2013 and Annex XIII "Tools for Analysis of a Future Energy Revolution: Methodologies, Tools and Data Bases" currently running from 2014-2016. The results of ETSAP-TIAM studies have wide diffusion among the groups that assess climate mitigation policies, including the Intergovernmental Panel on Climate Change (IPCC). A scientific report on the improved calibration of China was submitted to all IEA ETSAP partners and discussed during two bi-annual meetings in 2014. Improvements of the IEA-ETSAP TIAM model included the correction of China's primary energy demand and final energy consumption based on improved statistical data and the inclusion of more renewable energy technologies for China. These China-specific changes in the global model impacted a wide range of power and industry sector technologies and processes, such as the modelling of carbon capture and storage (CCS) technologies for China under climate mitigation policy scenarios. These China-specific model improvements, in a long-term perspective towards 2100, resulted in an increased primary energy supply for China (from about 300 EJ to 350 EJ) and in increased total final energy consumption (from 280 EJ to 310 EJ) in the baseline scenario. Corresponding global CO_2 emissions under the baseline scenario increased from about 60 Gt to 62 Gt. This highlights the importance of sufficiently cross-checked and updated China-specific data in global energy models and the global impacts of energy system changes in China with regards to global energy consumption and modelled CO_2emissions.

5.3. Public outreach

Public outreach activities during this research were numerous, as these were a pre-requisite to establish a new bilateral Sino-Danish research collaboration and an ongoing dialogue with Chinese energy sector colleagues. Public outreach activities included (i) two research-based consulting activities upon the request of IRENA and the German National Academy of Science and Engineering acatech; (ii) the development of a professional website including a personal China energy blog; and (iii) the participation in international energy conferences in Europe and in China.

A professional energy website, including a China energy blog, was launched in the summer of 2013 and maintained throughout the research period (www.peggymischke.com). This website served as an interactive platform, in addition to the ad-hoc workshop-based teachings in China and conference participations in Europe and China. Publicly available workshop materials and conference presentations were posted online as soon as possible. Daily and monthly visitors, both new and existing, increased in particular during China research stays. About 15000 visitors were attracted to the website in the year of 2014, with an increasing trend, as indicated in **Figure 13**. **Publication A – Chinese and IEA energy statistics** was published open-access in October 2013 and was posted on a popular Chinese micro-blog after a few days. It stimulated a debate on China's energy statistics, as shown in **Figure 14**.

Figure 13: Early public outreach statistics from my personal website.

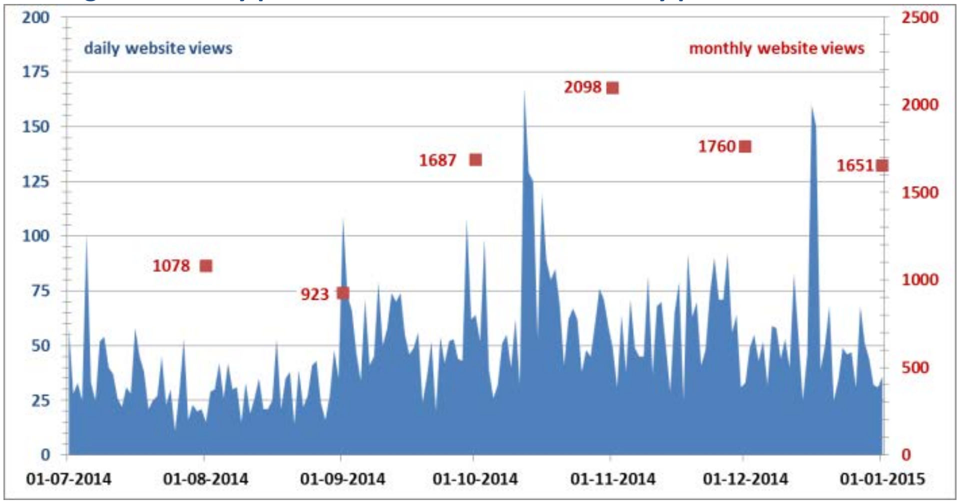
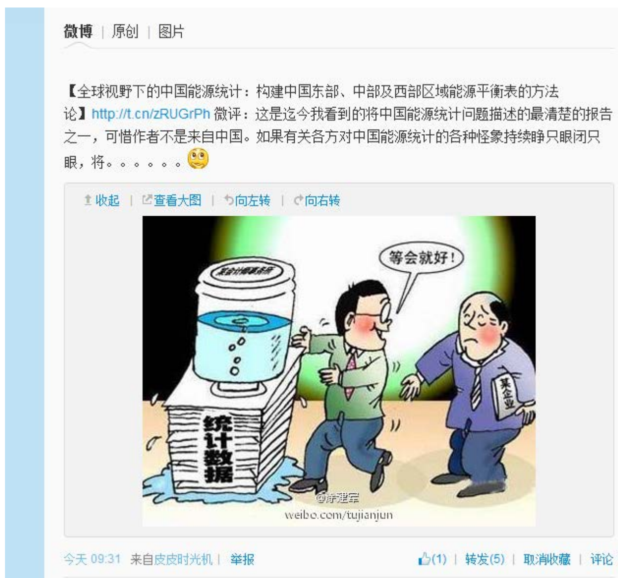


Figure 14: Chinese social media discussion of Publication A – Chinese and IEA statistics.



5.4. Outlook

This research should be seen as a starting point of a new bilateral Sino-Danish research collaboration. No large prior knowledge, networks, China expertise available “in-house” at the beginning of this three year PhD research project. The different perspectives for analysing China’s “energy revolution” presented here could be thus be expanded and improved with more details in many new research areas.

Future avenues of research could include a more detailed analysis of major national energy and climate policies in China and their regional impacts. Much uncertainty remains about the future path of China’s energy sector and the full nature and the scale of associated impacts, such as climate change. More transparent and comparable scenario analysis in collaboration with Chinese energy experts will be beneficial to advance the discussion of the nationally intended commitments for climate change mitigation by China and other countries and what domestic and global impacts those might have. The new air pollution policies released in several provinces of East-China, East-to-West regional economic development policies and carbon tax policies could be analysed in this regard. This would benefit from more collaborative work in identifying, selecting and translating national, provincial, and power-grid specific policies in China into sets of main regional policy instruments that can be modelled globally. A more detailed set of plausible storylines for regional energy sector developments in China needs to be developed and discussed. Such global research is usually carried out by larger multi-disciplinary teams collaborating across different countries, and the new collaborations established here, could serve as a starting point for joint research projects in this regard.

More comparative analysis between China and other emerging countries with similar coal based energy systems, such as India and South Africa, could be interesting. Cross-country research on common energy and climate policies, such as nationally proposed climate change mitigation commitments, could advance the debate on the challenges and opportunities of emerging economies in climate change mitigation and adaptation. Such studies could be very useful to provide inputs to the upcoming global climate change negotiations at the next UNFCCC Conference of the Parties (COP) in Paris, France, in December 2015. Consistent and complete energy data sets for emerging economies will be a challenge in this regard, thus increased collaboration is strongly recommended.

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Appendices: main PhD publications

China's energy statistics in a global context: A methodology to develop regional energy balances for East, Central and West China

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MPRA Working Paper Nr. 50305

1st October 2013

Published open access at the University of Munich MPRA repository

http://mpra.ub.uni-muenchen.de/id/eprint/50305

Table of Content

Tables and Figures

A.1. Summary

Reliable, timely and accurate energy data are critical to carry out analysis of energy system changes. An energy balance, characterizing fuels/commodities in energy supply, transformation and sectoral end uses is an essential tool to calibrate energy system models. China’s economy and energy system progressed rapidly over the past decade. Current structural changes include shifts from central planning to markets; from agriculture to services/manufacturing; from rural to urbanized; and from national to globalized. An improved understanding of the quality and reliability of Chinese economic and energy data is becoming more important to understanding global energy markets and future greenhouse gas emissions. China's national statistical system to track such changes is however still developing and, in some instances, energy data remain unavailable in the public domain.

The 2007 UNFCCC Bali Action Plan[1] highlighted the need to make national emissions trends and reductions for all countries measurable, reportable, and verifiable. Internationally comparable energy indicators and statistics are released from multiple international institutions, including the United Nations, the World Bank and the International Energy Agency (IEA). With a highly-qualified staff of around 220 the IEA is one of the best-equipped public multilateral energy institutions specialised in energy statistics and related policy advice. The IEA’s World Energy Outlook (WEO) is widely regarded as one benchmark/reference of global energy data analysis and policy scenarios for the future global energy markets. China is currently not one of the Non OECD IEA member countries and China‘s national system of statistical classification varies in some degree from international norms.

In order to allow for a comparative analysis and research about the fast pace development of China's energy system in an international context, a simplified methodology to build regional energy balances for China is needed. This working paper reviews China's energy statistics in view of identifying suitable energy system indicators to develop a simplified regional energy balance for China from a variety of publicly available data. As China's national statistical system continuous to be debated and criticised in terms of data quality, comparability and reliability, an overview of the milestones, status and main issues of China's energy statistics is given. In a next step, the energy balance format of IEA is used as an international benchmark to analyze China's national energy statistics in detail and identify indicators to establish regional energy balances inside China. Although this methodology includes a range of data uncertainties, it is intended to stimulate the discussion about current and future regional energy system developments in China in a broader global context. More international comparable and transparent research is needed to better understand and assess China’s progress toward meeting energy supply security targets and emission reduction goals, both at a regional, national and global level.

[1] The 2007 Climate Change Conference (the 13th Conference of the UNFCCC Parties) in December 2007 in Bali culminated in the adoption of the Bali Road Map and the Bali Action Plan, including decisions and resolutions for a new negotiating process designed to tackle climate change. See: http://unfccc.int/key_steps/bali_road_map/items/6072.php

A.2. China's energy statistics in a global context

A.2.1. Milestones in the development of China's energy statistical system

China's statistical system, as other Chinese administrations, departed from a top-down planned economy with several hierarchical levels for data collection and reporting. Since the elaboration of China's first five year plan in 1953, quantitative indicators were established by the central government to plan and measure economic growth and industrial output, such as coal and steel production. The main focus then was to develop large scale production bases in for instance iron and steel manufacturing, coal mining, cement production, electricity generation, and machine building.

China's energy statistical system started in the 1980s under the 6th five year plan. In the 1980s, the central government created a large set of rules, standards, and methods for formulation physical energy intensity standards, such as the amount of fuel and electricity used per ton of industrial product (Sinton 1988). In 1978 China began implementing a system of energy supply by quota. All enterprises required certification to receive annual allotments of fuels and electricity. Most commercial energy and other industrial commodities were allocated and distributed through a limited set of channels and a small number of mainly industrial users accounted for most consumption. The initial regulations on statistical work for trial implementation by the State Council in 1963 were replaced by a statistical law in 1984. Already in 1982 a special energy statistics institution was set up inside China's statistical system. In 1985 the energy statistics started data collection and reporting for energy production and consumption based on all economic units of the planned economy. In 1986 the first specialized energy statistical year book was released.

China's statistical system received less attention as central planning weakened in the 1990s. With the introduction of reforms to open up and introduce market mechanisms in the planned economy under China's 8th five year plan, the central government's control over allocation of many products (including energy) weakened. Energy statistics were affected by understaffing and underfunding in particular at lower administrative levels. Attention to energy issues declined furthermore, as energy availability was no longer considered to be a critical constraint on economic growth in general. Surveys required to complement traditional bottom up reporting were cut back (LBNL 2001, WB 2007). With the allocation of fuels through markets, flows of energy became more difficult to monitor and analyze in China's statistical system. Bilateral statistical corporation started and as a novelty the State Statistical Bureau's general statistical yearbook was published in its first bilingual English-Chinese edition in 1994.

In the 2000s China's statistics received frequent critics relating to data quality and reliability issues. China's entry into the World Trade Organization in 2001 reinforced the shift to market economics and intensified urbanization in the mainly urban centres along the coast. In November 2003, the then Chinese Premier Wen Jiabao called for “urgent improvement of statistical system and methodology in order to increase the accuracy, timeliness and scientific nature of statistical data and to enhance the authority of official statistics” (China Daily 2003). Regular budgetary appropriations to publish energy statistics beyond the few indicators that appear in the China Statistical Yearbook were not available (LBNL 2001). In 2007 only four staff members in NBS worked on China's energy statistics at the country level and only half of China's provinces had one staff member for energy statistics (WB 2007). The 10th five year plan targeted the development of a national statistical information network. A revised statistical law was enacted in 1996, designing the National Bureau of Statistics (NBS), formerly the State Statistical Bureau, as the officially national authority and primary source for China's statistical information in general and energy related statistics in particular (PRC 1996). New census degrees for industry and agriculture were implemented in 2004 and 2006 to complement traditional bottom up information collection.

China is the largest energy consuming and greenhouse gas emitting country in the world today. Frequent discussion on China's energy statistics are taking place, in the context of the country's accelerated industrialization and urbanization which required more energy-intensive products. In line with international climate change negotiations, targets for emission intensity reduction and energy efficiency were incorporated besides traditional economic growth and production increase targets under the 11th and 12th five year plans. The 11th five year plan furthermore called for expanding international scientific and technology cooperation, including staff exchange programs with international statistical agencies. NBS has implemented a number of international cooperation programs terms of database development, data processing, statistical training and international harmonization. Statistical information released from NBS currently serves as a basis for China's statistical co-operations with IEA, the UN statistical division, the US Department of Energy, British Petroleum Statistical Review of World Energy, the World Bank's World Development Indicators and other international institutions. Several bilateral collaboration projects are ongoing to build consistent international methodologies for various energy statistical issues, e.g. US collaboration with NDRC to establish methods to assess biomass resources in China (ACORE 2012).

A.2.2. Data collection methods

China today has a hybrid statistical system that is in a transition phase as China's economy keeps restructuring. Incomplete energy sector reforms and the persistence of some structural features characteristic of the planning system remain present in statistics. The growth of the economy, the extensions in the statistical coverage of sectors of economic activity previously omitted, and the introduction of new statistical methods have led to a rapid increase in the size of the statistical system. Statistics developed during the planning economy are planned to be cut off by while new and improved statistics on resources, environment, services, etc, will be introduced.

Statistical data published by the National Bureau of Statistics (NBS) are the declared standard data for China. The National Bureau of Statistics (NBS) is responsible for organizing and coordinating official statistics nationwide and to formulate statistical standards, as stipulated in the statistical law. Many international organizations that report national energy figures for China rely on NBS and its sources. NBS is combining various data collection methods, such as traditional bottom up reporting through several administrative levels, infrequent national censuses and some data estimates/adjustments.

A.2.2.1. Bottom up reporting

China's large national statistical system consists of statistical bureaus under governments at all levels as per the administrative principle of centralized leadership and decentralized responsibility. This network connects NBS under the central government, provincial statistical bureaus under provincial, municipality and autonomous region governments, prefecture statistical bureaus under prefecture governments, and county statistical bureaus under county governments. In 2007 the governmental statistical system included 887 counties and employed an estimated number of 72000 staff. Of these less than 20 percent were employed directly by NBS at the central level and 10 percent were engaged at the provincial level, with the remaining majority of staff distributed between prefectures/cities and counties. In terms of educational qualification, about 30 percent had degree level education (UNSD 2007).

An automated system of statistical information reporting is still under development. The regular published energy statistics by NBS depend on bottom up reporting from provincially controlled statistical offices, which in turn rely on lower-level local branches in creating their energy accounts. At the lowest administrative level, the county and township bureau of statistics are responsible for data collection from all public enterprises and agencies within their geographic administrative boundaries. As stipulated in the statistical law enterprises are responsible to adhere to state or local statistical investigation tasks and establish and improve their information management systems for checking, transferring and filing statistical data. In February 2012 the NBS launched a unified data collection system through which covers 700,000 major companies can send their data directly to the government's statistics centre or authorized provincial branches (Xinhua 2013).

NBS standards for bottom up reporting only cover enterprises above a designated size. NBS collects energy data directly from industrial enterprises. Large energy production enterprises must report their information to the NBS once a month and small energy production enterprises report once a quarter. Measurements of electricity, natural gas, and heat use—which are metered and invoiced by utilities—are not used directly for statistical reporting (Carnegie 2010). Many smaller firms in the industry and service sector with annual revenues below 5 million Chinese RMB (USD $730,000) were excluded from bottom up reporting in 2004. The bottom up reporting in 2008 only covered 10% of China's enterprises (Carnegie 2010). The definition of industrial enterprises above a designated size was revised upwards in 2012, requiring reporting when revenue from principal business exceeds 20 million RMB (NBS 2012).

Besides NBS some ministries and centralized government departments are authorized to provide further data for national accounting. With relevance for energy data, these include the General Administration of Customs (statistics on imports and exports), Ministry of Commerce (statistics on foreign investment), Ministry of Environmental Protection (statistics on environmental protection), Ministry of Agriculture (biomass statistics) and the Ministry of Land and Resources (statistics on geological prospecting and reserves).

A.2.2.2. National census and surveys

The new economic census was designed to survey the development of the secondary and tertiary industries in China and establish a sound information system of enterprise registers and related data. The 2004 first economic census merged the previously separated census of manufacturing industries, the census of service industries and the census of establishments, and included the construction sector as an additional category. All major energy intensive industries are thus covered by this new economic census including mining, manufacturing, construction, electricity and water supply, and service industries. The statistical method of complete enumeration is the principle of the economic census as stipulated in the economic census degree of 2004. The First National Economic census was conducted during 2004-2006 with a budget of over 3 billion yuan, employing about 10 million enumerators for data collection[2]. Economic census will be conducted once in every five years. A second national economic census followed in 2009.

A new agriculture census was carried out in 2006 as per the agricultural census degree. The scope of the Agricultural Census included farm crops planting, forestry, animal husbandry, fishery and services rendered to these industries. The contents of the agricultural census included many dispersed activities in rural areas of China, including the utilization of agricultural land, rural labour force and employment, rural infrastructural facilities, rural social services, livelihood of farmers, and environment situation. Agricultural census will be conducted once in every ten years.

[2] In comparison the last population census carried out in 2010 employed 6 million enumerators. The budget for this 6th population census was estimated at 700 million yuan. Source: Branigan, Tania (November 1, 2010). "China census could be first to record true population". The Guardian. Accessed on August 20, 2013. http://www.theguardian.com/world/2010/nov/01/china-census-true-population

A.2.3. Estimates and historic data adjustments

China’s annual statistics are intended to cover all economic activity, but NBS has better access to information from bottom up reporting in some end use sectors than in others. Since the 1990s the portion of economic activity within the control of government has shrunk, and with it the ability of the NBS to gather data, gradually eroding the completeness and accuracy of bottom up statistics. For end-use sectors dominated by a few, large state-owned entities, like the iron and steel industry, reliable bottom up statistics on consumption are available. In some other sectors, however, there is only a thin statistical basis for gathering energy use statistics without detailed national surveys, especially those in which non-state enterprises are more numerous or changing frequently. Estimates occur for instance for energy consumption of many small locally owned/controlled power plants, refineries, mines and other installations at lowest administrative levels is usually estimated by local officials and renewable rural energy use, where only a few surveys with limited sample sizes are occasionally carried out (LBNL 2001, WB 2007). To a large extend NBS cannot independently verify data accounts from bottom up reporting.

National bottom up statistics based on provincial reports need to be adjusted by NBS. This includes methods to account for differences in quality of coal mined and used in different places and to eliminate double counting of industrial activities covering several provinces. Furthermore data from autonomous regions and special administrative regions are not fully integrated with the provincial statistics of mainland China. Statistical data reported from Hong Kong and Macau, which are two special administrative regions of China, is not part of energy statistics. Statistical data from the Tibet Autonomous Region are rarely reported to NBS, these are generally lacking from national statistics when no estimates are carried out.

The results from the two recent economic censuses led to wide ranging historic data adjustments, in particular for coal data. After the first national economic census several historical statistical data from 1993 onwards were revised. Another round of historic data adjustment followed the results of the second national economic census in 2010. In the early 1990s China's unadjusted energy statistic reported a growing gap between coal production and use, indicating missing coal supply in the range of 200 million tons annually (LBNL 2001). Energy production, consumption and energy intensity data for the period of 1998 – 2003 where adjusted upwards due to previous underreporting of coal data following China's reorganization of the coal mining sector under the 10th 5YP. Researchers related this unreported production to small coal mines that were forced to close by a central government decision, but might have re-opened unofficially. The largest historic coal data revision following the second economic census was an addition of 149 million tonnes coal equivalent (Mtce) to the total primary energy consumption in 2007 (LBNL 2007), including an increase of industry final coal use in 2007 by 130 mtce. Furthermore the second census changed once more some of the energy-related data that were already adjusted in the first census, then resulting in a smoother curve for energy consumption after 1996 (Carnegie 2010).

A.2.4. Data availability and data providers

Since the development of China's energy statistical system in the 1980s, the amount and variety of statistical materials about China‘s energy system continues to increase. Frequently data on China's energy system are published in the format of a statistical yearbook, which in a printed edition contains numerous pages with data tables for different energy indicators at a national and sub-national level. China's statistical material published to date is vast, covering for example more than 50 annual statistical yearbooks for 2012. Each statistical yearbook usually includes at least 400 pages in its printed edition. As most statistics in China are not considered to be public goods, the purchasing prizes per yearbook vary over a wide range from USD 70-1640 for the latest edition. The general national statistical yearbook alone is extensive and consists of more than 4000 data tables on more than 1000 pages to describe the state of the country's overall economy, including basic energy production, residential urban and rural energy statistics and energy imports/exports. The statistical yearbook is released annually in September and contains the whole year statistical data of the previous year. A publicly accessible online NBS Database is at the trial stage since 2007, it mainly contains data from the general statistical yearbook[3]. Figure A-1 below shows the increase of national statistical yearbooks in China since the 1980s.

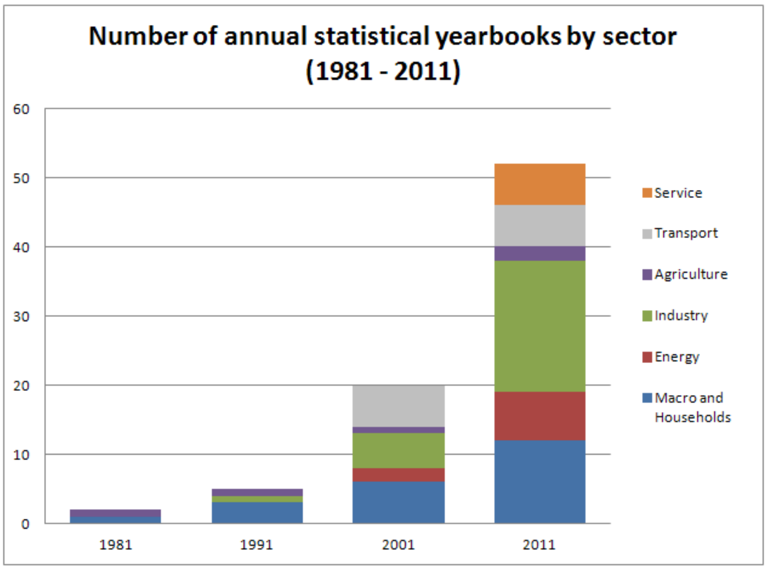


Figure A-1: Increase of national statistical yearbooks in China (1981-2011)

The number of data providers besides NBS is increasing. Many industry associations, including the China Building Materials Industrial Association, the China Automotive Industry Association and the China Nonferrous Metals Industry Association, and other high level government institutions, such as NDRC, are publishing energy related statistical yearbooks in parallel to NBS. Increased competition among governmental and private data providers can result in the publication of very similar statistical yearbooks for a sector, such as the Yearbook of the Industrial Economy (published since 1991 by NBS) and the Yearbook of the Industry Economy (published since 2005 by the China Financial and Economic Publishing House affiliated with the People´s Bank of China).

In order to analyse China's energy system data in a comprehensive way, energy indicators scattered in several statistical yearbooks and estimates for data gaps based on expert judgement need to be combined. Energy statistics appear primarily in the following yearbooks published by NBS that have a long tradition and are available in recent bilingual English-Chinese editions: China Statistical Yearbook, China Energy Statistical Yearbook, and the Statistical Yearbook of China’s Industrial Economy. However most energy sector specific data remains published in Chinese and needs to be purchased, thus limiting wide scale public access. Provincial energy balances are published in the Energy Statistical Yearbook (and not the Statistical Yearbook), providing an important view of changes in demand and supply in China‘s widely divergent regions. Sub-sectoral breakouts of industrial energy use are only published at the national level. Coal production and use can be estimated by using several sources of information, such as output by coal type, region, and ownership, however detailed information on the coal quality by coal type is usually not available to the public (Carnegie 2010). Sometimes the format of the published data makes it difficult to analyze them efficiently in databases

[3] http://219.235.129.58/welcome.do (accessed September 15, 2013)

without additional formatting. Sometimes statistical categories are unclear as these lack detailed explanation and comparison to internationally commonly used definitions.

The access to and use of company related commercial data and data relating to state secrets remains highly restricted. The 2002 statistical law specifies that "[…] whoever makes use of statistical investigation to steal state secrets or violates the provisions of this [Statistical] Law regarding the maintenance of secrets shall be punished according to provisions of relevant laws […]" (PRC 1996). As no definition of state secrets is included in legal documents, a lot of uncertainty and ambiguity exists with regards to confidential energy statistics. Many information sources often are unable or unwilling to provide much detail beyond what lies in the public domain (LBNL 2001).

A.2.5. Data quality issues

China's statistical capacity and statistical systems is challenged by the size and complexity of the country's energy institutional and administrative framework. NBS data revisions reflect the difficulties of maintaining data accuracy in a rapidly changing, increasingly decentralized economy where information remains highly politicized (WB 2007). The total statistical effort is both too large to manage with the existing technology and skill levels at the sub-national level, and is subject to local pressure (WB expert 2002). NBS cross-checks energy supply data on the basis of enterprise output sales and energy production data once a year (Carnegie 2010).

Concerns about the quality of Chinese energy statistics are longstanding and have received frequent critical international attention over the past years. One example of a prominent dispute about the quality of China's energy data occurred in 2010: China's government disagreed initially with the International Energy Agency's assessment that China already surpassed the U.S. as the world's largest energy consumer in 2009, claiming IEA data are not very reliable. Economic and energy data play a critical role in China's policymaking, because indicators for economic growth and coal energy use will directly affect China's energy and emission intensity in various end use sectors and thus national and international climate change commitments. The effect of the 2010 energy and GDP revisions on energy intensity was judged by some China observers as a move to facilitate China's Eleventh Five Year Plan target of 20% reduction between 2005 and 2010. The Chinese state owned press recently reported about a case of economic data manipulation about by a county government in southwest China's Yunnan Province (Xinhua 2013). Some China observers suggest that provincial data are affected by local authorities' desire to show higher economic growth rates in their region (Carnegie 2010).

Many official energy data are released by Chinese authorities in aggregated format and with considerable delays. Much of NBS's statistical information is only available in aggregated form at the national level, e.g. summary reports for all State Owned Enterprises of a certain company size. NBS issues quarterly data by industrial firm size category for internal government use (Carnegie 2010). China's 2nd official communication to UNFCCC in 2012 used 2005 as a base year for energy and GHG emission related data. A delay until 2010 in publishing Chinese energy data for 2008 raised data quality questions among many China observers (Carnegie 2010). Similarly, the publicly available aggregated energy balance of China for 2011 is released on IEA's public website since September 2013[4].

Differences in statistical definitions and break in series make comparative analysis and independent reviews difficult and time consuming. Assessing energy resources and reserves from Chinese statistics in an international context is challenging, as statistical terms are partly defined broader than according to international norms. In Chinese statistics fossil energy resources include fossil energy deposits under all

[4] http://www.iea.org/stats/balancetable.asp?COUNTRY_CODE=CN, accessed August 20, 2013 and September 20, 2013

possible geological conditions, belonging to all geological ages, and proven geological reserves include proven reserves and also reserves that cannot be recovered economically or do not meet operating conditions. Break in series and change in statistical categories for coal production from major coal mining enterprises occurred during 2003-2006, nearly doubling the total coal production from below 600 million tons to above 1000 million tons. Breaks in series for passenger vehicles and trucks occurred in 2002, making comparisons of transport data with previous years more challenging. As of 2002 different coke qualities reported separately are aggregated in a national coke production figure. Disaggregated statistical information relating to single power plants is hardly available, for instance a hydro power plant capacity and power generation by province/location was last published in 1991. As of 2006 disaggregated pipeline data for oil and gas were no longer published in the NBS Statistical Yearbook.

China’s energy statistics should be treated as a starting point for policy analysis and uncertainties should be clearly spelled out. As the quality of China's coal statistics is critized, China's electricity production (and consumption) is a widely used unofficial indicator for measuring the state of the country’s economy (NYT 2012). Confidence in the quality of data for natural gas, hydropower and nuclear power is higher, as no major revisions occurred during the past two censuses. IEA and US DoE also highlight in several of their recent publications of China's coal data, that China's internal coal statistics are often inconsistent, requiring careful crosschecking and caution for analysis. This unreliability has major implications because coal production and use dominate all important aggregate Chinese energy data, including total energy consumption, energy intensity of the GDP, and carbon dioxide emissions. A prominent issue is that China's national energy balance sheet is not balancing with the sum of the countries provincial balance sheets. Official statistics are not necessarily always accurate, but they are the only comprehensive starting point for analyzing China's national energy system. While energy statistics were probably relatively good in the early 1990s, their quality has declined since the mid-1990s. Recently the quantity of statistical data sources and information providers increased considerably. As NBS data plays a role in Chinese policymaking, analyses and international collaboration based on NBS data are important for improving its accuracy and for providing common ground for policy research.

A.3. A triangulation method to develop regional energy balances for East, Central and West China

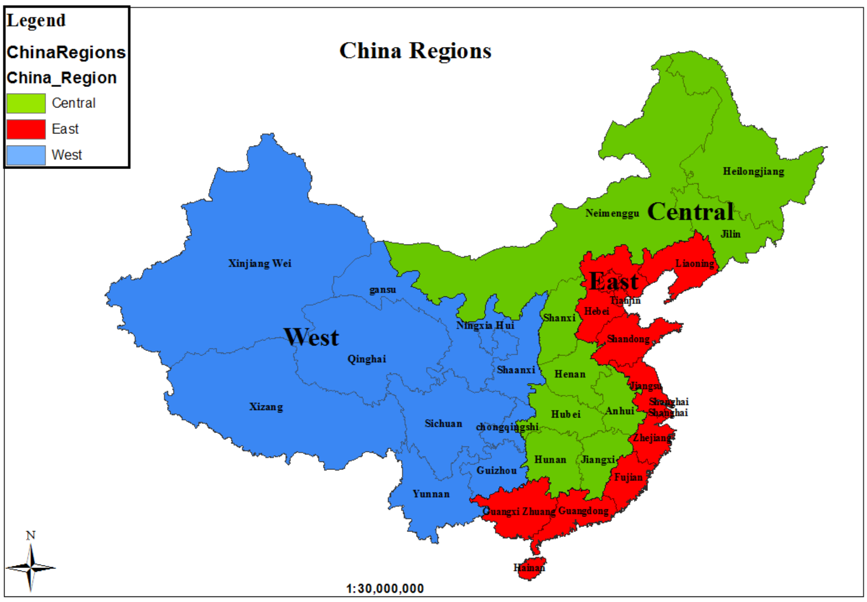
Based on the current status of China's statistical system and the available public energy data, a new triangulation method of different closely related international and Chinese energy statistics is proposed to build bottom up regional energy balances of China in an international context. While this triangulation approach will include some expert judgement to fill data gaps, it at least offers more insights into regional energy dynamics in China in a transparent way. As discussed before, the preliminary energy data now available in China are insufficient to confidently assign numbers to every energy indicators of interest for energy policy analysis. As China's statistical office currently does not plan to align their national standard for accounting of economic activities to international best practise before 2020, a transparent tool to understand, assess and compare China's national and provincial energy statistics in an international context is required.

Use a national IEA energy balance of China as a starting point. The IEA energy balance will serve as a benchmark and ensure international comparison of statistical categories. IEA's national energy balances for about 100 non-OECD countries, including China, are published annually in September. The unit to compare total energy is ton oil equivalent. IEA's energy balance format distinguishes primary energy supply, energy transformation, energy industry own use and final energy use for up to 60 fuels and energy commodities. The IEA energy balance format will include fuel re-allocations in different sectors based on long term experience from IEA China energy data experts. For example the analysis of China's transportation energy use does require revisions to NBS's statistics, including re-allocations of petroleum products from agriculture, industry and service sector to the transport sector (LBNL 2001).

Assign the energy commodities in all categories of China's provincial energy balance to the IEA energy balance. China's national and provincial energy balance tables and detailed national breakouts of sectoral energy end use are published by NBS usually in September one year after the primary energy statistics are released. China’s main fuel is coal and the unit to compare total energy is standard ton coal equivalent. China's national energy balance includes primary energy supply, in- and output of fuels and energy commodities in transformation, losses, and final consumption for 32 fuels and energy commodities. It is commonly understood that China‘s system of statistical classification varies in some degree from international norms. International comparisons and detailed analysis of the data do require making adjustments; many times this is based on expert judgment due to limited statistical reporting categories and energy data confidentiality in China. Energy indicators are analyzed in their physical values to minimize statistical differences due to different conversion factors.

Identify regions in China with different energy system characteristics to build bottom up energy balances for different regions in China from provincial energy data. The suggested regional definition of China is based on the Seventh Five-Year Plan (1986–1990), which grouped all provincial level divisions of China[5] into three economic zones in order to promote medium to long term economic specialization and division of labour (see Figure A-2). China researchers refer to similar regional divisions of China by regrouping provincial energy and economic data, when analysing disparities within China (Carnegie 2008). A similar regional classification is currently used in some of the official Chinese economic and energy statistics[6].

Figure A-2: A regional division of China's energy system in East, Central and Western Regions



[5] The People's Republic of China administers 33 Provincial level divisions, including 22 provinces, five autonomous regions, four municipalities, and two Special administrative regions.

[6] The main difference between the presented regional divisions of China is that a North Region is defined in addition to east, central and west China regions. The north is based on three provinces only (Liaoning, Heilongjiang, Jilin).

- The **China East Region** consists of Liaoning, Beijing, Tianjing, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Hainan and Guangxi[7]. This region specialized since the 1980s in export-oriented industries, including steel, chemicals, engineering and textiles. In 2010 about 578 million inhabitants (44% of Chinese population) lived on 13% of China's land area. The China East Region is currently the economic powerhouse of the country, accounting for more than 92% of China's exports and about 97% of China's GDP in 2010 (NBS 2011; Economist 2012). China's fast economic growth resulted in widening disparities in regional developments and incomes, and increase in domestic migration trends towards China's coastal provinces (WB 2006). This regional population density is high with an average 448 persons/km2. The eastern-coastal provinces have higher emissions but lower emissions intensities than the central and western provinces.
- The **China Central Region** consists of Heilongjiang, Jilin, Inner Mongolia, Shanxi, Henan, Anhui, Hubei, Hunan and Jiangxi. This region contains most of China's coal and metallurgical industries, as well as agricultural production. In 2010 about 440 million inhabitants (34% of Chinese population) lived on 29% of China's land area. Although the share of China's GDP was only 2% for these provinces in 2010, this region is crucial for supplying the provinces in China's East Region.
- Finally, the **China Western Region** consists of Shaanxi, Gansu, Ningxia, Xinjiang, Qinghai, Sichuan, Guizhou and Yunnan[8]. In 2010 about 293 million inhabitants (22% of Chinese population) lived on 57% of China's land area, resulting in a low population density of 53 persons/km2. This part of China continues to be the least developed region, with a marginal share of about 1% in China's GDP in 2010. The major hydropower resources are located in the Western Region of China including Tibet. The western provinces have limited emissions but higher emissions intensities than the eastern coastal provinces.

Calculate regional shares from various provincial energy data to calibrate regional energy balances from a national benchmark. The use of regional shares for East, Central and West China, derived from bottom up provincial energy statistics for the most important energy commodities, has the advantage that those can be applied to a consistent and internationally comparable national energy balance of China (here the IEA China energy balance is used as a national benchmark).

Use closely related statistics and expert assumptions to check consistency and fill data gaps. In addition to NBS's provincial energy balances information from Chinese industry yearbooks, periodicals, and government websites as well as international organisations will be screened to fill data gaps. For consistency check fuel consumption in a given sector could be compared to output and energy intensities that are reported in Chinese statistics. Feedback from Chinese energy researchers will be provided to further minimize uncertainty and improve the regional modelling of China in a global context.

[7] Data on Hong Kong and Macau are excluded, as these follow different statistical systems and are not part of NBS provincial energy balances.
[8] Data on Tibet are excluded due to NBS data gaps.

A.4. Indicators for modelling regional energy balances of China

A.4.1. Indicators for primary energy supply

The IEA energy balance data for primary energy supply are compared to Chinese provincial data from provincial energy balances and alternative data where required. On this basis it is possible to establish detailed and international comparable indicators for regional primary energy shares for East, Central and West China.

IEA energy balance – primary energy supply

The total primary energy supply of a country in the IEA energy balance is calculated from indigenous production, accounting for fuel imports/exports and changes in fuel stocks held on the national territory. In line with international conventions, fuels for ships and aircrafts for international navigation and aviation are excluded from the national energy balance and reflected in the global energy balance. For the 2005 China IEA energy balance data are available for the following primary energy sources: hard coal, oil and petroleum products natural gas, primary solid bio-fuels and biogases, nuclear and hydro electricity. China coal data are aggregated as hard coal and oven coke in IEA statistics - this includes different coal qualities of anthracite, coking coal, other bituminous coal and sub-bituminous coal.

China provincial energy balance – primary energy supply

Primary energy production and use are among most frequently reported of China’s energy statistics. Typically, aggregate primary energy production and use for a given year are reported the following year in metric tons of standard coal equivalent. The accuracy of overall energy statistics is particularly dependent on the accuracy of coal output figures. Statistics on oil production and use are much better characterized than for coal. On the production side, the three major state owned oil companies produce most of China’s crude, and a few dozen refineries produce over 90% of China’s oil products (LBNL 2001). The bulk of China’s oil imports come from crude oil and fuel oil. Much of this fuel oil is used in power plants along the southern coast, where coal transported from northern China is less competitive. Natural gas information comes from just a few sources, and travels through heavily monitored pipelines and port facilities. Contrary to international statistics the fuels used by Chinese planes and ships in international aviation and navigation is included in imports (NBS 2012).

Alternative provincial energy data – primary energy supply

While many official Chinese sources deal with commercial energy sources, there is relatively little information on renewable energy. NBS excludes the production of fuels of low calorific value, bio-energy and solar energy from its energy balances. Measuring renewable energy sources – besides large scale hydropower – is relatively new in China. Data on wind power generation is included since 2010 in the statistical yearbook. Data on biomass energy use by province have been published in some editions of the China Energy Statistical Yearbook, covering wood, crop wastes, and biogas. These are based on estimates provided by the Ministry of Agriculture in the China Rural Energy Yearbook and should only be taken as a rough guide for rural non-commercial energy activities (LBNL 2001).

<u>Conclusions – primary energy supply</u>

In general NBS provincial energy data from NBS energy yearbook can be used for a regional energy balance in primary energy supply. If data for several fuels are provided in Chinese statistics, the data of the fuel that dominates primary energy supply is applied, for instance raw coal is the key fuel for hard coal primary energy supply.

The following assumptions based on alternative data sources were made to establish regional energy balances for China (see Table A-1 below for further details):

- Crude oil production shares by region were taken from the petroleum industry yearbook (and not the energy yearbook) to account for production from off-shore oilfields in different regions.
- Primary electricity production in China's provincial energy balances was cross-checked with nuclear and hydro-power production to include a more detailed primary electricity supply by energy source.
- The indicator of agricultural grain production is used to assume regional shares for primary biomass energy supply in China.
- Fuels that appear in energy transformation in IEA's energy balance, but are already listed under primary energy in Chinese statistics, are not treated here. This includes coal gases, refined petroleum products and fossil electricity and heat.

Table A-1: Regional energy balance of China – primary energy supply

Primary energy supply – IEA energy balance	**Primary energy supply – NBS provincial energy balance**	**Primary energy supply – alternative provincial data**	**Key Indicator – EAST CHINA**	**Key Indicator – CENTRAL CHINA**	**Key Indicator – WEST CHINA**
Coal and coal products					
Hard coal: Indigenous production International import International export	**Raw coal, cleaned coal, other washed coal, briquettes:** Production Imports (international, interprovincial) Exports (international, interprovincial)	Coal throughput of coastal ports, total coal imports; total coal exports (China Customs Bureau)	**Raw coal:** Production: 16% International import: 100% International export: 100%	**Raw coal:** Production: 59%	**Raw coal:** Production: 25%
Coke: International import International export	**Coke, other coking products:** Production Imports (international, interprovincial) Exports (international, interprovincial)		**Coke:** International import: 100% International export: 100%	n.a.	n.a.
n.a.	**Blast furnace gas, coke oven gas, converter gas, other gas:** Recovery of energy Imports (interprovincial) Exports (interprovincial)		n.a.	n.a.	n.a.
Oil and petroleum products					
Crude oil Indigenous production International import International export	**Crude oil:** Production Imports (international, interprovincial) Exports (international, interprovincial)	Crude oil production by oil field from major three SOE (Petroleum industry yearbooks)	**Crude oil:** Production incl. offshore fields: 80% International import: 86% International export: 100%	**Crude oil:** Production by field: 8%; International import: 8%	**Crude oil:** Production by field: 12% International import: 6%
NGL: Indigenous production	n.a.	Crude oil production by oil field from major three SOE (Petroleum industry yearbooks)	**Crude oil:** Production incl. offshore fields: 80%	**Crude oil:** Production by field: 8%;	**Crude oil:** Production by field: 12%
LPG: International imports International exports	**LPG:** Imports (international, interprovincial) Exports (international, interprovincial)		**LPG:** Import: 100% Export: 100%	n.a.	n.a.
Motor gasoline: International exports	**Gasoline:** International exports		**Gasoline:** Export: 100%	n.a.	n.a.
Other kerosene: International imports International exports	**Kerosene:** Imports (international, interprovincial) Exports (international, interprovincial)		**Kerosene**: Import: 100% Export: 100%	n.a.	n.a.
Gas/diesel oil: International imports International exports	**Diesel oil:** Imports (international, interprovincial) Exports (international, interprovincial)		**Diesel oil:** Import: 100% Export: 100%	n.a.	n.a.
Fuel oil: International imports International exports	**Fuel oil:** Imports (international, interprovincial) Exports (international, interprovincial)		**Fuel oil:** Import: 100% Export: 100%	n.a.	n.a.
n.a.	**Naphtha, lubricants, petroleum coke, petroleum waxes:** Imports (international, interprovincial) Exports (international, interprovincial)		n.a.	n.a.	n.a.
Non-specified oil products: International imports International exports	**Other petroleum products:** Imports (international, interprovincial) Exports (international, interprovincial)		**Other petroleum products:** Import: 86% Export: 100%	**Other petroleum products:** Import: 8%	**Other petroleum products:** Import: 6%
Natural gas					
Natural gas: Indigenous production International export	**Natural gas:** Production Imports (international, interprovincial) Exports (international, interprovincial)		**Natural gas:** Production: 13% Exports: 100%	**Natural gas:** Production: 5%	**Natural gas:** Production: 83%
n.a.	**LNG:** Production Imports (international, interprovincial) Exports (international, interprovincial)		n.a.	n.a.	n.a.
Bio-Energy					
Primary solid biomass: Indigenous production	n.a.	Grain production (NBS YB)	**Grain production:** 31%	**Grain production:** 50%	**Grain production:** 19%
Biogas: Indigenous production	n.a.	Grain production (NBS YB)	**Grain production:** 31%	**Grain production:** 50%	**Grain production:** 19%
Electricity and Heat					
Nuclear electricity: Indigenous production	n.a.	National gross nuclear electricity generation (NBS YB) in combination with IEA reports	**Nuclear generation:** 100%	n.a.	n.a.
Hydro electricity: Indigenous production	n.a.	Hydro power generation (NBS YB)	**Hydro generation:** 22%	**Hydro generation:** 30%	**Hydro generation:** 48%
Primary electricity: International imports International export	**Primary electricity:** Production Imports (international, interprovincial) Exports (international, interprovincial)		n.a.	**Electricity generation:** Import: 36%	**Electricity generation:** Import: 64% Export: 100%
n.a.	**Heat:** Recovery of energy		n.a.	n.a.	n.a.

A.4.2. Indicators for energy transformation

The IEA energy balance data for energy transformation are compared to Chinese provincial data from provincial energy balances and alternative data where required. On this basis it is possible to establish detailed and international comparable indicators for regional shares for energy transformation in East, Central and West China.

IEA energy balance – energy transformation

In the IEA energy balance transformation processes comprise the conversion of primary forms of energy to secondary and further processes (e.g. coking coal to coke, crude oil to oil products, and fuel oil to electricity). The main transformation processes appearing in the IEA China energy balance are electricity and heat plants, blast furnaces, gas works, coke ovens, patent fuel plants and oil refineries.

- So defined **main activity producers for electricity and heat** are included in energy transformation section of the IEA energy balance, as these generate electricity and heat from primary energy for sale to third parties as their main activity. Private or publicly owned entities that generate electricity and heat wholly or partly for their own use to support their primary activity are called **auto-producers** instead. No data on co-generation is given in China's national energy balance.
- **Coke ovens** are included under transformation, as these produce coke and coke oven gas from hard coal (coking coal). Primary energy inputs to large scale industrial **blast furnaces** are included under energy transformation. This includes for example blast furnaces for the Iron and Steel Industry. The production of pig-iron from iron ore in blast furnaces uses fuels for supporting the blast furnace charge and providing heat and carbon for the reduction of the iron ore. The transformation component is shown in the row blast furnaces in the column appropriate for the fuel, and the consumption component is shown in the row iron and steel, in the column appropriate for the fuel. Accounting for the calorific content of the fuels entering the process is a complex matter as transformation (into blast furnace gas) and consumption (heat of combustion) occur simultaneously. Some carbon is also retained in the pig-iron; almost all of this reappears later in the oxygen steel furnace gas (or converter gas) when the pig-iron is converted to steel. The IEA suggests an energy transformation efficiency of 40% for the corresponding fuel for cross checks. Three different process stages for steel manufacturing – from coal to steel – provide three different coal based gas types: coke gas, blast furnace gas and converter gas. Primary energy inputs to manufacture town gas from hard coal in **gas works** is included in transformation. As a by-product of hard coal gas coke is produced here that can be used for heating.
- **Patent fuel plants** are included, as these manufacture the so called patent fuels from hard coal fines with the addition of a binding agent, the output are often called briquettes.
- **Oil refineries** are included under energy transformation as these manufacture a wide range of finished petroleum products from crude oil.

China provincial energy balance – energy transformation

Energy transformation that is reported in China's provincial energy balance relates to processes rather than technologies (see Annex A-2). The sub-categories in energy transformation do not fully match IEA's categories, for example coal transformation processes, such as coal washing and briquette production, are China-specific.

Alternative provincial data – energy transformation

Data from international institutions, such as IEA, were used to cross-check the status of infrastructure for main energy transformation processes. Data suggest that main refining activity takes place in the coastal provinces, as crude oil input and different refined petroleum products output indicate. There are 21 large scale refineries in three areas in East China (Yangtze River Delta, Pearl River Delta and Bohai Rim) with total refinery capacity of around 270 Mt/year, accounting for 47% of the total refining capacity (IEA 2010). Major coal transformation processes are taken place in the central region, as this also is the area with most abundant coal reserves (IEA 2009). Natural gas is explored in different regions in China, both off-shore and onshore, and a few major national gas pipelines are available to provide gas supply from West to East. China started importing LNG in 2006 only and has now five operational LNG terminals in operation in the eastern coastal provinces (IEA 2010).

Electricity production from fossil fuels and nuclear, both main and auto-producers, is concentrated in the East, as this region hosts the key industrial development zones. Hydro electricity however is dominant in the West, the region of China with the most abundant water resources. There are seven different power grids in China managed by different state owned electricity companies. IEA estimated that 540000 km of transmission lines above 35kV were operational in 1999 (IEA 2009). No fully interconnected national electricity grid exists currently and interconnections between regional grids remain weak. The national electrification rate is 98%. Lack of electricity access is limited to the West Region, where many off grid technologies are traditionally used when no connection to the Southern China Power Grid exists.

Conclusions – energy transformation

NBS provincial energy data need to be combined with alternative data sources to establish a regional energy balance in energy transformation. If data for several fuels are provided in Chinese statistics, the data of the fuel that dominates primary energy supply is applied, for instance raw coal is the key fuel for hard coal in energy transformation. The regional shares of energy transformation processes were cross checked with Chinese energy sector experts and seem in line with alternative data sources.

The following assumptions based on alternative data sources were made (see Table A-2 below for further details):

- Thermal electricity production in China's provincial energy balances was cross-checked with nuclear and hydro-power production to include more detailed electricity and heat indicators.
- The indicator of bio-waste based power production in China's urban areas was used to assume regional shares for biomass related transformation process to produce power and heat.
- Fuels that appear in primary energy in Chinese statistics were allocated here, for example production of coal gases, coke, and refined petroleum products.

Table A-2: Regional energy balance of China – energy transformation

Energy transformation - IEA energy balance	Energy transformation – NBS provincial energy balance	Energy transformation – alternative provincial data	Key Indicator – EAST CHINA	Key Indicator – CENTRAL CHINA	Key Indicator – WEST CHINA
Coal and coal products					
Hard coal: Input for main electricity plants Input for main heat plants Input for coke ovens Input for gas works Input for patent fuel plants	**Raw coal, cleaned coal, other washed coal, briquettes, gangue:** Input for thermal power Input for heating supply Input for coking Input for gas works Input for and output from coal washing Input for and output from briquettes production	Briquette production for patent fuel plants (NBS YB)	**Raw coal:** input power plants:47%; input heat plants:59%; input gas works:21%; **Cleaned coal:** input coking: 39%; **Briquette** output: 58%	**Raw coal:** input power plants: 36%; input heat plants: 31%; input gas works: 68%; **Cleaned coal:** input coking: 47%; **Briquette** output: 27%	**Raw coal:** input power plants: 17%; input heat plants: 10%; input gas works: 11%; **Cleaned coal:** input coking: 13% **Briquette** output: 18%
Oven Coke: Input for gas works Input for coke ovens Output from coke ovens	**Coke, other coking products:** Input for gas works Output from coking Output from gas works	Coke production (NBS YB)	**Coke:** input gas works: 34%; output coking: 35%	**Coke:** input gas works: 65%; output coking: 36%	**Coke:** input gasworks: 1%; output coking: 19%
Gas coke: Output from gas works	**Coke, other coking products:** Output from gas works		**Coke:** output gas works: 5%	**Coke:** output gas works: 18%	**Coke:** output gas works: 77%
Coke oven gas: Input for auto electricity plants Input for auto heat plants Output from coke ovens	**Coke oven gas:** Input for thermal power Input for heating supply Output from coking Output from gas works		**Coke oven gas:** input power plants: 51%; input heat plants: 40%; output coking: 42%	**Coke oven gas:** input power plants: 39%; input heat plants: 53%; output coking: 43%	**Coke oven gas:** input power plants: 10%; input heat plants: output coking: 15%
Blast furnace gas: Input for auto electricity plants Input for auto heat plants Output from blast furnaces	**Blast furnace gas:** Input for thermal power Input for heating supply Input for coking Output from gas works		**Blast furnace gas:** input power plants: 62%; input heat plants: 60%; input coking: 64%;	**Blast furnace gas:** input power plants: 32%; input heat plants: 30%; input coking: 36%; output gas works:100%	**Blast furnace gas:** input power plants: 6%; input heat plants: 10%;
Gas works gas: Output from gas works	n.a.	Other gas output from gas works (NBS YB)	**Other coal gas:** output gas works: 35%	**Other coal gas:** output gas works: 62%	**Other coal gas:** output gas works: 3%
n.a.	**Converter gas, other gas:** Input for thermal power Input for heating supply Input for coking Input for and output from gas works		n.a.	n.a.	n.a.
Oil and petroleum products					
Crude oil: Input for auto electricity plants Input for auto heat plants Input for refineries	**Crude oil:** Input for thermal power Input for heating supply Input for refineries		**Crude oil:** Input power: 96%; Input heat: 100%; Input refineries: 71%	**Crude oil:** Input power: 4%; Input refineries: 14%	**Crude oil:** Input refineries: 15%
Refinery gas: Input for auto electricity plants Input for auto heat plants Output from refineries	**Refinery gas:** Input for thermal power Input for heating supply Input for gas works Input for and output from refineries		**Refinery gas:** Input power: 68% Input heat: 38% Output refineries: 71%	**Refinery gas:** Input power: 15% Input heat: 39% Output refineries: 16%	**Refinery gas:** Input power: 17% Input heat: 23% Output refineries: 13%
LPG: Input for auto electricity plants Input for auto heat plants Output from refineries	**LPG:** Input for gas works Input for and output from refineries	LPG consumption in industry (NBS) for power/heat auto-producers	**LPG:** Input power: 74%; Input heat: 74%; Output refineries: 60%	**LPG:** Input power: 18% Input heat: 18% Output refineries: 27%	**LPG:** Input power: 8% Input heat: 8% Output refineries: 13%
Motor gasoline, aviation gasoline: Output from refineries	**Gasoline:** Output from refineries		**Gasoline:** Output refineries: 64%	**Gasoline:** Output refineries: 19%	**Gasoline:** Output refineries: 17%
Jet type fuel kerosene, other kerosene: Output from refineries	**Kerosene:** Output from refineries		**Kerosene:** Output refineries: 85%	**Kerosene:** Output refineries: 9%	**Kerosene:** Output refineries: 6%
Gas/diesel oil: Input for auto electricity plants Output from refineries	**Diesel oil:** Input for thermal power Input for heating supply Output from refineries		**Diesel oil:** Input power: 30%; Output refineries: 68%	**Diesel oil:** Input power: 60%; Output refineries: 15%	**Diesel oil:** Input power: 10%; Output refineries: 17%
Fuel oil: Input for main electricity plants Input for main heat plants Input for gas works Output from refineries	**Fuel oil:** Input for thermal power Input for heating supply Input for and output from refineries	Fuel oil consumption in industry (NBS) for gas works	**Fuel oil:** Input power: 93% Input heat: 81% Input gas works: 76% Output refineries: 82%	**Fuel oil:** Input power: 5% Input heat: 18% Input gas works: 20% Output refineries: 10%	**Fuel oil:** Input power: 2% Input heat: 1% Input gas works: 4% Output refineries: 8%
Naphtha, lubricants, bitumen, paraffin waxes, petroleum coke: Output from refineries	**Naphtha, lubricants, petroleum coke, petroleum waxes, bitumen asphalt, white spirits:** Output from refineries		**Naphtha:** Output refineries: 90%	**Naphtha:** Output refineries: 7%	**Naphtha:** Output refineries: 3%
Non-specified oil products: Output from refineries	**Other petroleum products:** Input for thermal power Input for heating supply Input for and output from refineries		**Other petroleum products:** Output refineries: 75%	**Other petroleum products:** Output refineries: 12%	**Other petroleum products:** Output refineries: 13%
Natural gas					
Natural gas: Input for main electricity plants Input for main heat plants	**Natural gas, LNG:** Input for thermal power Input for heating supply Input for natural gas liquefaction Input for gas works		**Natural gas:** Input power: 71% Input heat: 57%	**Natural gas:** Input power:15% Input heat: 22%	**Natural gas:** Input power:14% Input heat: 21%
Bio-Energy					
Biomass: Input for auto electricity plants Input for auto heat plants	n.a.	Urban power generation from bio-waste (NDRC)	**Urban power generation from bio-waste:** 75%	**Urban power generation from bio-waste:** 20%	**Urban power generation from bio-waste:** 5%
Electricity and Heat					
Nuclear electricity: Input for main electricity plants	n.a.	National gross nuclear electricity generation (NBS YB) and IEA reports;	**Nuclear generation:** 100%	n.a.	n.a.
Hydro electricity: Input for main electricity plants	n.a.	Hydro power generation (NBS YB),	**Hydro generation:** 22%	**Hydro generation:** 30%	**Hydro generation:** 48%
Electricity: Output from main electricity plants Output from auto electricity plants	**Electricity:** Output from thermal power		**Thermal power:** 46%	**Thermal power:** 37%	**Thermal power:** 17%
Heat: Output from main heat plants Output from auto heat plants	**Heat:** Output from heating supply		**Heat supply:** 52%	**Heat supply:** 38%	**Heat supply:** 10%

A.4.3. Indicators for energy industry own use

The IEA energy balance data for energy industry own use are compared to Chinese provincial data from provincial energy balances and alternative data where required. On this basis it is possible to establish detailed and international comparable indicators for regional shares for energy industry own use in East, Central and West China.

IEA energy balance – energy industry own use

Energy industry own use in the IEA energy balance covers the amount of fuels used by the energy producing industries (e.g. for heating, lighting and operation of all equipment used in the extraction process, for traction and for distribution). It includes primary and secondary energy consumed by energy industries for heating, pumping, traction and lighting purposes as per UN ISIC categories. Energy which is used directly within c**oal mines, oil and gas extraction, coke ovens, gas works, oil refineries and electricity/heat plants** is listed in sub-categories.

China provincial energy balances – energy industry own use

No data are provided, as there is no category for energy industry own use established (see Annex A-2 and A-4). Energy industry own use is reported as part of final energy use. Mining and oil and gas extracting is included in the mining industry in the national energy balance, without specifying the fuel share for energy industry own use. The production and distribution of electricity, heat and gas is also reported in final industry consumption at a national level, without specifying the fuel shares for energy industry own use. Figures for fuel use to operate electricity and heat plants are distributed among end-use sectors by using the gross heat rate of power generation to convert electricity to standard coal (LBNL 2001).

Alternative provincial data – energy industry own use

This section of the IEA energy balance requires alternative data for all fuels. As explained in Table 3 below, energy industry own use of the main fuel is related to other corresponding economic activities in the provincial energy balance (NBS). For example regional shares in raw coal production are assumed to specify regional shares of hard coal use in the coal mining industry.

Conclusions – energy industry own use

This section of the energy balance contains many assumptions due to lack of data. The suggested shares in Table A-3 were cross-checked with Chinese energy sector experts.

Table A-3: Regional energy balance of China – energy industry own use

Energy industry own use – IEA energy balance	Energy industry own use – NBS provincial energy balance	Energy industry own use – alternative provincial data	Key Indicator – EAST CHINA	Key Indicator – CENTRAL CHINA	Key Indicator – WEST CHINA
Coal and coal products					
Hard coal: Own use in coal mines Own use in coke ovens Own use in electricity and heat plants Own use in gas works	n.a.	Energy industry own use of the main fuel is related to other corresponding economic activities in the provincial energy balance (NBS)	**Raw coal:** Production: 16% Transformation loss: 17% Power plants: 47% Gas works: 21% **Cleaned coal:** Coking: 39%	**Raw coal:** Production: 59% Transformation loss: 2% Power plants: 36% Gas works: 68% **Cleaned coal:** Coking: 47%	**Raw coal:** Production: 25% Transformation loss: 82% Power plants: 17% Gas works: 11% **Cleaned coal:** Coking: 13%
Oven Coke: Own use in coal mines Own use in coke ovens Own use in electricity and heat plants Own use in gas works	n.a.	Energy industry own use of the main fuel is related to other corresponding economic activities in the provincial energy balance (NBS)	**Coke:** Coking: 35% Heat plants: 0% Gas works: 34%	**Coke:** Coking: 36% Heat plants: 100% Gas works: 65%	**Coke:** Transformation loss: 100% Coking: 19% Heat plants: 0% Gas works: 1%
Gas coke: Own use in gas works	n.a.	Energy industry own use of the main fuel is related to other corresponding economic activities in the provincial energy balance (NBS)	**Coke:** Gas works: 34%	**Coke:** Gas works: 65%	**Coke:** Gas works: 1%
Coke oven gas: Own use in coal mines Own use in coke ovens Own use in electricity and heat plants Own use in gas works	n.a.	Energy industry own use of the main fuel is related to other corresponding economic activities in the provincial energy balance (NBS)	**Coke oven gas:** Transformation loss: 50% Coking: 42% Power plants: 51%	**Coke oven gas:** Coking: 43% Power plants: 39% **Blast furnace gas:** Gas works: 100%	**Coke oven gas:** Transformation loss: 50% Coking: 15% Power plants: 10%
Gas works gas: Own use in gas works	n.a.	Energy industry own use of the main fuel is related to other corresponding economic activities in the provincial energy balance (NBS)	**Other coal gas** Gas works: 35%	**Other coal gas** Gas works: 62%	**Other coal gas** Gas works: 3%
Oil and petroleum products					
Crude oil Own use in oil and gas extraction	n.a.	Energy industry own use of the main fuel is related to other corresponding economic activities in the provincial energy balance (NBS)	**Crude oil:** Production: 44%	**Crude oil:** Production: 46%	**Crude oil:** Production: 30%
Refinery gas: Own use in refineries	n.a.	Energy industry own use of the main fuel is related to other corresponding economic activities in the provincial energy balance (NBS)	**Refinery gas:** Refineries: 71%	**Refinery gas:** Refineries: 16%	**Refinery gas:** Refineries:13%
LPG: Own use in oil and gas extraction Own use in gas works Own use in refineries	n.a.	Energy industry own use of the main fuel is related to other corresponding economic activities in the provincial energy balance (NBS)	**LPG:** Transformation loss: 99% Gas works: 99% Refineries: 60%	**LPG:** Refineries: 27%	**LPG:** Gas works: 1% Refineries: 13%
Motor gasoline: Own use in electricity and heat plants	n.a.	Energy industry own use of the main fuel is related to other corresponding economic activities in the provincial energy balance (NBS)	n.a.	n.a.	**Gasoline:** Power plants: 100%
Other kerosene: Own use in coal mines Own use in oil and gas extraction Own use in refineries non specified	n.a.	Energy industry own use of the main fuel is related to other corresponding economic activities in the provincial energy balance (NBS)	**Kerosene:** Transformation loss: 92% Refineries: 85%	**Kerosene:** Refineries: 9%	**Kerosene:** Transformation loss: 8% Refineries: 6%
Gas/diesel oil: Own use in coal mines Own use in oil and gas extraction Own use in electricity and heat plants Own use in gas works Own use in refineries	n.a.	Energy industry own use of the main fuel is related to other corresponding economic activities in the provincial energy balance (NBS)	**Diesel oil:** Transformation loss: 85% Power plants: 30% Refineries: 68%	**Diesel oil:** Transformation loss: 6% Power plants: 60% Refineries: 15%	**Diesel oil:** Transformation loss: 9% Power plants: 10% Refineries: 17%
Fuel oil: Own use in coal mines Own use in oil and gas extraction Own use in electricity and heat plants Own use in gas works Own use in refineries	n.a.	Energy industry own use of the main fuel is related to other corresponding economic activities in the provincial energy balance (NBS)	**Fuel oil:** Transformation loss: 100% Power plants: 93% Gas works:76% Refineries: 82%	**Fuel oil:** Power plants: 5% Gas works:20% Refineries: 10%	**Fuel oil:** Power plants: 2% Gas works:4% Refineries: 8%
Natural gas					
Natural gas: Own use in oil and gas extraction Own use in electricity and heat plants Own use in gas works Own use in refineries	n.a.	Energy industry own use of the main fuel is related to other corresponding economic activities in the provincial energy balance (NBS)	**Natural gas:** Transformation loss: 48% Power plants: 71% Gas works:100%	**Natural gas:** Transformation loss: 14% Power plants: 15%	**Natural gas:** Transformation loss: 36% Power plants: 14%
Electricity and Heat					
Electricity: Own use in coal mines Own use in oil and gas extraction Own use in electricity and heat plants Own use in coke ovens Own use in refineries	n.a.	Energy industry own use of the main fuel is related to other corresponding economic activities in the provincial energy balance (NBS)	**Electricity:** Transformation loss: 54%	**Electricity:** Transformation loss: 23%	**Electricity:** Transformation loss: 23%
Heat: Own use in coal mines Own use in oil and gas extraction Own use in electricity and heat plants Own use in coke ovens Own use in refineries	n.a.	Energy industry own use of the main fuel is related to other corresponding economic activities in the provincial energy balance (NBS)	**Heat:** Transformation loss: 64%	**Heat:** Transformation loss: 36%	n.a.

A.4.4. Indicators for final energy consumption

The IEA energy balance data for final energy consumption are compared to Chinese provincial data from provincial energy balances and alternative data if required. On this basis it is possible to establish detailed and international comparable indicators for regional shares for energy consumption in East, Central and West China. Appendices A-2 to A-5 provide additional information on the structure of IEA and Chinese provincial energy balances.

Final consumption in IEA's energy balance is all fuel and energy that is delivered to the consumption sectors, both for use as for energy needs and non–energy needs. Consumption sectors comprise industry (excluding the energy industry), commerce and public administration, agriculture, forestry and fishing, residential and other non-specified fuel consumption by other consumers (including military). As discussed before, any fuel consumption by consumers which is used for electricity and heat generation for sale is reported as part of the transformation sector in the IEA energy balance format.

China's provincial energy balances have limited detail on final energy consumption and the reported aggregated fuel mix might be misleading in comparison with international statistical energy end use categories. Final end use subsectors that report aggregated final energy use in the provincial energy balances of China are industry; construction; farming, forestry, animal husbandry, fishery conservancy; transport, storage, post; wholesale, retail trade, hotel, restaurants; residential consumption and other (referring to public institutions such as schools, hospitals, and the military). Fuels in total energy consumption include coal, crude oil and petroleum products, natural gas and electricity. As in primary energy supply, the consumption of fuel of low calorific value, bio-energy and solar energy is excluded from energy statistics.

As a main difference to international energy statistics, many energy end use categories in China's statistical system are sorted by their institutional arrangement (e.g. ownership of goods and companies) and not by economic activity and purpose. In the 2012 NBS statistical yearbook more than 10 different reporting categories for enterprise ownership were established[9]. Large state-owned enterprises in rural areas are often major providers of social services. Some large, integrated steel plants provide housing, education, and social services, and run a variety of ancillary activities from trucking to publishing to restaurants and hotels, in addition to the core business of manufacturing iron and steel products (LBNL 2001). Energy consumption statistics from enterprises in industrial (and other) sectors includes therefore a certain amount of activity that belongs in other sectors as per international statistical standards.

A.4.4.1. Industry

IEA energy balance - Industry

The industry classification in the IEA energy balance follows the UN International Standard Industrial Classification of All Economic Activities (ISIC). ISIC is one international reference classification of productive activities. Its main purpose is to provide a set of activity categories that can be utilized for the collection and reporting of statistics according to such activities. Since the adoption of the original version of ISIC in 1948, the majority of countries have used ISIC as their national activity classification or have developed national classifications derived from ISIC.

[9] Enterprise ownership categories include amongst others state-owned enterprises; collective owned enterprises; cooperative entities; joint ownership entities; limited liability corporations; shareholding corporations; private enterprises; other domestic funded entities; enterprises with sole foreign investment; other enterprises with foreign funds

The industry sector in IEA's energy balance specifies the use of fuels within the **manufacturing and construction industries**, excluding fuels used in energy industries (under energy industry own use), solid fuels use for coke manufacture and in blast furnaces within the iron and steel sector (under transformation) and fuels consumed for the transport of goods (under transport sector). Major energy consuming industries in China are iron and steel industry; chemical and petrochemical industry; non-ferrous metals industry, non-metallic minerals industry and paper, pulp and print industry. Less energy intensive industry sub-sectors include for instance food and tobacco, wood and wood products, textile and leather, machinery, transport equipment.

China provincial energy balance - Industry

China's Industrial Classification for National Economic Activities (ICNEA) is used to specify industry end uses in China's national and provincial energy balances. While the ICNEA is derived from ISIC many aggregations and breakdowns are defined according to China specific national conditions. The latest ICNEA revision was carried out in 2011, it is planned to revise the current version within 8 – 10 years.

Industrial energy use by energy type for over thirty industrial subsectors is available for China. This series exists only on a national (and not at the provincial) level, and begins in 1980. Industry refers to the material production sector in the extraction of natural resources and processing and reprocessing of minerals and agricultural products. The three main sub-categories in China's industry classification are (i) mining, (ii) manufacturing and (iii) electric power, gas, water production and supply. Mining includes the mining and transformation of coal and the extraction of petroleum and natural gas. Under manufacturing more than 30 sub-divisions exist. Major energy consuming categories under manufacturing include the smelting and pressing of ferrous and non-ferrous metals; the manufacturing of raw chemical materials and chemical products; the manufacturing of non-metallic mineral products; the manufacturing of metal products; and the processing of petroleum, nuclear fuel and coking. In addition the construction sector is separated from the industry sector, while it is included in industry in the IEA energy balance. Contrary to international best practice NBS includes statistics from enterprises in energy-producing sectors as well as for energy-consuming sectors under energy consumption (and not under energy transformation).

Alternative provincial energy indicators - Industry

For China the accuracy of overall energy statistics is particularly dependent on the accuracy of industry end use figures in heavy, energy intensive industries. Coal is the main fuel for industry consumption in China and the majority (87% in 2010) is untreated raw coal.

China's major economic zones are located in the eastern coastal provinces around Beijing, in the Pearl river delta around Hong Kong, in the Yangtze river delta around Shanghai and in the area west of Taiwan street. General industrial activity in different regions of China can be cross-checked with alternative provincial energy indicators that deal with statistics about economic development zones, employment or enterprise ownership by industry. Some statistical indicators for general industry activity from various data sources are:

- Provincial distribution of large SOEs (NBS YB);
- Provincial distribution of private enterprises (NBS YB);
- Provincial distribution of free trade zones, high tech industrial development zones and economic and development zones (World Bank and Asian Development Bank research reports);
- Employment in construction and manufacturing by SOEs and private enterprises by province (NBS YB);

- Provincial distribution of top 1000 energy consuming enterprises under 11th 5YP (US LBNL research reports).

The outputs of key industrial, energy intensive products can also be used to assume China's industrial energy end use. A few energy-intensive industrial products determine a very large share of the country's coal demand, and thus total energy demand. One ton of coal equivalent is needed to manufacture for example 0,6 tons of synthetic ammonia; 1,5 tons of steel; or 6,6 tons of cement (NBS 2012).

Conclusions - Industry

NBS provincial energy data need to be combined with alternative data sources to establish a regional energy balance in final energy consumption in industry. The following assumptions based on alternative data sources were discussed with Chinese energy sector exports (see Table A-4 below for further details):

- China accounted for nearly 40% in world steel production in 2010 (World Steel Association 2011). Crude steel output is chosen as it's the key output from iron and steel industry. It is matched with all main fuels, as no fuel specific data are provided in NBS statistics.
- China's cement industry accounts for about 10% of industrial final energy consumption (LBNL 2011). Cement is thus chosen as the key energy indicator to assume regional shares in the non-ferrous metal industry.
- Fertilizers are the main output of the chemical and petrochemical industry. Share of fertilizer outputs are used to derive regional fuel shares in chemical and petrochemical industry.
- Regional shares of Paper and paperboard output outputs are used to derive regional fuel shares in the pulp, paper and printing industry.
- Aluminium production and output are not reported in NBS statistics. Therefore the fuel consumption in the industry sector in general is chosen as main indicator for the non-metallic mineral industry.

Table A-4: Regional energy balance of China – final consumption in Industry

Industry final consumption – IEA energy balance	**Industry final consumption – NBS provincial energy balance**	**Industry final consumption – alternative provincial data**	**Key Indicator – EAST CHINA**	**Key Indicator – CENTRAL CHINA**	**Key Indicator – WEST CHINA**
Coal and coal products					
Hard coal: Iron and Steel Industry Chemical and petrochemical Industry Non-ferrous Metal Industry Non-metallic Mineral Industry Pulp, paper and printing Industry Non-specified Industry	**Raw coal, washed coal, other cleaned coal, briquettes, gangue:** Industry Construction	Production of crude steel (Steel Industry YB, NBS YB); Fertilizer output (NBS YB); Cement output (NBS YB); Output of paper and paperboard (NBS YB);	**Raw coal:** Crude steel output: 64% Fertilizer output: 25% Cement output: 45% Industry: 43% Paper & –board output: 70% Industry: 43%	**Raw coal:** Crude steel output: 26% Fertilizer output: 41% Cement output: 33% Industry: 37% Paper & –board output: 23% Industry: 43%	**Raw coal:** Crude steel output: 10% Fertilizer output: 34% Cement output: 22% Industry: 20% Paper & –board output: 7% Industry: 43%
Oven Coke: Iron and Steel Industry Chemical and petrochemical Industry Non-ferrous Metal Industry Non-metallic Mineral Industry Pulp, paper and printing Industry Non-specified Industry	**Coke and other coking products:** Industry Construction	Production of crude steel (Steel Industry YB, NBS YB); Fertilizer output (NBS YB); Cement output (NBS YB); Output of paper and paperboard (NBS YB);	**Coke:** Crude steel output: 64% Fertilizer output: 25% Cement output: 45% Industry: 56% Paper & –board output: 70% Industry: 56%	**Coke:** Crude steel output: 26% Fertilizer output: 41% Cement output: 33% Industry: 29% Paper & –board output: 23% Industry: 29%	**Coke:** Crude steel output: 10% Fertilizer output: 34% Cement output: 22% Industry: 15% Paper & –board output: 7% Industry: 15%
Coke oven gas: Iron and Steel Industry Chemical and petrochemical Industry Non-ferrous Metal Industry Non-metallic Mineral Industry Pulp, paper and printing Industry Non-specified Industry	**Coke oven gas:** Industry Construction	Production of crude steel (Steel Industry YB, NBS YB); Fertilizer output (NBS YB); Cement output (NBS YB); Output of paper and paperboard (NBS YB);	**Coke oven gas:** Crude steel output: 64% Fertilizer output: 25% Cement output: 45% Industry: 39% Paper & –board output: 70% Industry: 39%	**Coke oven gas:** Crude steel output: 26% Fertilizer output: 41% Cement output: 33% Industry: 45% Paper & –board output: 23% Industry: 45%	**Coke oven gas:** Crude steel output: 10% Fertilizer output: 34% Cement output: 22% Industry: 16% Paper & –board output: 7% Industry: 16%
Blast furnace gas: Iron and Steel Industry	**Blast furnace gas, converter gas, other gas:** Industry Construction	Production of crude steel (Steel Industry YB, NBS YB);	**Blast furnace gas:** Crude steel output: 64%	**Blast furnace gas:** Crude steel output: 26%	**Blast furnace gas:** Crude steel output: 10%
Oil and petroleum products					
LPG: Iron and Steel Industry Chemical and petrochemical Industry Non-ferrous Metal Industry Non-metallic Mineral Industry Pulp, paper and printing Industry Non-specified Industry	**LPG:** Industry Construction	Production of crude steel (Steel Industry YB, NBS YB); Fertilizer output (NBS YB); Cement output (NBS YB); Output of paper and paperboard (NBS YB); LPG network length (NBS YB)	**LPG:** Crude steel output: 64% Fertilizer output: 25% Cement output: 45% Industry: 74% Paper & –board output: 70% Industry: 74%	**LPG:** Crude steel output: 26% Fertilizer output: 41% Cement output: 33% Industry: 18% Paper & –board output: 23% Industry: 18%	**LPG:** Crude steel output: 10% Fertilizer output: 34% Cement output: 22% Industry: 8% Paper & –board output: 7% Industry: 8%
Gas/diesel oil: Iron and Steel Industry Chemical and petrochemical Industry Non-ferrous Metal Industry Non-metallic Mineral Industry Pulp, paper and printing Industry Non-specified Industry	**Diesel oil:** Industry Construction	Production of crude steel (Steel Industry YB, NBS YB); Fertilizer output (NBS YB); Cement output (NBS YB); Output of paper and paperboard (NBS YB);	**Diesel oil:** Crude steel output: 64% Fertilizer output: 25% Cement output: 45% Industry: 65% Paper & –board output: 70% Industry: 65%	**Diesel oil:** Crude steel output: 26% Fertilizer output: 41% Cement output: 33% Industry: 21% Paper & –board output: 23% Industry: 21%	**Diesel oil:** Crude steel output: 10% Fertilizer output: 34% Cement output: 22% Industry: 14% Paper & –board output: 7% Industry: 14%
Fuel oil: Iron and Steel Industry Chemical and petrochemical Industry Non-ferrous Metal Industry Non-metallic Mineral Industry Pulp, paper and printing Industry Non-specified Industry	**Fuel oil:** Industry Construction	Production of crude steel (Steel Industry YB, NBS YB); Fertilizer output (NBS YB); Cement output (NBS YB); Output of paper and paperboard (NBS YB);	**Fuel oil:** Crude steel output: 64% Fertilizer output: 25% Cement output: 45% Industry: 76% Paper & –board output: 70% Industry: 76%	**Fuel oil:** Crude steel output: 26% Fertilizer output: 41% Cement output: 33% Industry: 20% Paper & –board output: 23% Industry: 20%	**Fuel oil:** Crude steel output: 10% Fertilizer output: 34% Cement output: 22% Industry: 4% Paper & –board output: 7% Industry: 4%
Ethane: Chemical and petrochemical Industry Non-specified Industry	n.a.	Fertilizer output (NBS YB);	**Ethane:** Fertilizer output: 25%	**Ethane:** Fertilizer output: 41%	**Ethane:** Fertilizer output: 34%
n.a.	**Naphtha, Lubricants, Petroleum waxes, white spirits, bitumen asphalt, other petroleum products:** Industry Construction		n.a.	n.a.	n.a.
Natural gas					
Natural gas: Iron and Steel Industry Chemical and petrochemical Industry Non-ferrous Metal Industry Non-metallic Mineral Industry Pulp, paper and printing Industry Non-specified Industry	**Natural gas, LNG:** Industry Construction	Production of crude steel (NBS YB); Fertilizer output (NBS YB); Cement output (NBS YB); Output of paper and paperboard (NBS YB);	**Natural gas:** Crude steel output: 64% Fertilizer output: 25% Cement output: 45% Industry: 30% Paper & –board output: 70% Industry: 30%	**Natural gas:** Crude steel output: 26% Fertilizer output: 41% Cement output: 33% Industry: 21% Paper & –board output: 23% Industry: 21%	**Natural gas:** Crude steel output: 10% Fertilizer output: 34% Cement output: 22% Industry: 49% Paper & –board output: 7% Industry: 49%
Electricity and Heat					
Electricity: Iron and Steel Industry Chemical and petrochemical Industry Non-ferrous Metal Industry Non-metallic Mineral Industry Pulp, paper and printing Industry Non-specified Industry	**Electricity:** Industry Construction	Production of crude steel (Steel Industry YB, NBS YB); Fertilizer output (NBS YB); Cement output (NBS YB); Output of paper and paperboard (NBS YB);	**Electricity:** Crude steel output: 64% Fertilizer output: 25% Cement output: 45% Industry: 55% Paper & –board output: 70% Industry: 55%	**Electricity:** Crude steel output: 26% Fertilizer output: 41% Cement output: 33% Industry: 28% Paper & –board output: 23% Industry: 28%	**Electricity:** Crude steel output: 10% Fertilizer output: 34% Cement output: 22% Industry: 17% Paper & –board output: 7% Industry: 17%
Heat: Iron and Steel Industry Chemical and petrochemical Industry Non-ferrous Metal Industry Non-metallic Mineral Industry Pulp, paper and printing Industry Non-specified Industry	**Heat:** Industry Construction	Production of crude steel (Steel Industry YB, NBS YB); Fertilizer output (NBS YB); Cement output (NBS YB); Output of paper and paperboard (NBS YB);	**Heat:** Crude steel output: 64% Fertilizer output: 25% Cement output: 45% Industry: 69% Paper & –board output: 70% Industry: 69%	**Heat:** Crude steel output: 26% Fertilizer output: 41% Cement output: 33% Industry: 22% Paper & –board output: 23% Industry: 22%	**Heat:** Crude steel output: 10% Fertilizer output: 34% Cement output: 22% Industry: 9% Paper & –board output: 7% Industry: 9%

A.4.4.2. Transport

IEA energy balance - Transport

IEA's transportation sector represents the fuels and energy used in the transport of goods and persons regardless of the economic sector to which it is contributing in line with ISIC specifications. Sub-categories in the transport sector according to transport modes are road, rail, domestic navigation, domestic aviation and pipeline transport. Pipeline transport includes fuel and energy used in the support and operation of pipelines transporting gases, liquids, slurries and other commodities. It comprises the consumption at pumping stations and for maintenance of the pipeline. Losses occurring during the transport between distributor and final are reported as distribution losses. Appraisal of China’s transportation energy use in an international context requires estimating revisions to NBS’s figures. One commonly used method for re-allocating gasoline use and portions of diesel use from other sectors to transport is as follows: 20% of agricultural diesel use, 10% of industrial diesel use, and 12% of service sector diesel use (LBNL 2011).

China provincial energy balance - Transport

The transport final consumption category in China's provincial energy balance is merged with storage and post/telecommunication. Transport sector data in NBS energy balances are collected from a wide range of sources, including the Ministry of Railways, Ministry of Transport, Civil Aviation Administration of China, the divisions of vehicle management under the provincial departments of public security of the Ministry of Public Security. Pipeline network statistics are mainly supplied by the respective state owned enterprises, such as the China National Petroleum and Natural Gas Corporation Group and the China Petrochemical Corporation Group.

Many Chinese specific definitions appear in the transport sector energy use, when comparing them with international statistics. A China specific characteristic of transport sector statistics is that vehicles are classified primarily by their function into civil or special vehicles. Civil vehicles include passenger vehicles and trucks for commercial transportation, vehicles owned by private enterprises and government institutions, and private vehicles. Vehicles for special purpose include fire trucks, municipal sanitation service vehicles, and military vehicles. Since 2002, the statistical standard of detail item of passenger vehicles and trucks, other vehicles have been revised, the data are not comparable with previous years. A major deficiency is the reporting of up to 50% of transportation energy use in other final end use sectors’ statistics due to NBS's reporting methods and sectoral definitions (LBNL 2001). Only energy use from enterprises whose main business activity is classified as transport is reported. Industrial and agricultural enterprises, as well as individuals operate a large fraction of China’s motor vehicles, and their consumption of motor fuels is reported as industrial, agricultural, or household consumption.

Alternative provincial energy indicators - Transport

A general indication of the regional development of transport infrastructure is given in national and provincial statistics about the length of rail, road and pipeline networks. Historically the country's rail network was vital to transport coal from major coal mining bases to the load centres in the eastern coastal provinces. Many coal power bases have rail access in near distance. The average coal and coke by rail transport distance in China was 642 km and 990 km in 2010 (NBS 2012). A Stanford study estimated the economic threshold for transporting coal by rail in China at 1200 km (Stanford 2010). Most of the rail locomotives continue to be coal-fired while the length of electrified railway tracks is increasing steadily. Currently about 10% of the railway lines are electrified.

Taking the indicator rail network length a homogenous rail network coverage of China is visible – of more than 93000 km of rail lines 31% are operational in East; 43% in Central and 26% in West China. A similar pattern is shown when the indicator road network length is taken – of more than 4 million km of roads 30% are operational in East; 37% in Central and 33% in West China (aggregating all road categories from dirt roads to highways). About 85000 km of express highways are included, but these are limited mainly to East and Central China (40% and 37% of express highway road km respectively). With regards to shipping by inland waterways, this transport mode is mainly feasible in East and Central China, where 47% and 33% of the 125000 km of inland waterways are operational.

The oil and natural gas pipeline network expansion shows the efforts to connect distant, resource rich provinces in China with the coastal provinces. About 40000 km of natural gas pipelines; 20000 km of crude oil pipelines and 18000 km of refined petroleum product pipelines are operational in China (IEA 2009). China's first national East West gas pipeline was completed in 2004; it required 890 km to connect the Ordos Basin in Inner Mongolia province with Beijing. A second national East West gas pipeline of 3900 km was built in 2009; this connects the Tarim Basin in Xingjian with Shanghai (IEA 2009). More than 50% of the natural gas network is operational in the East coastal provinces (NBS 2012).

Conclusions - Transport

NBS provincial energy data need to be combined with alternative data sources to establish a regional energy balance in final energy consumption in the transport sector. As aggregated transport data from Chinese statistics might be misleading, the following assumptions were discussed and agreed on with Chinese energy sector exports (see Table A-5 below for further details):

- Freight weight distance for different transport modes are used as an alternative indicator to assume final fuel consumption in different regions of China
- Passenger weight distance shares for different transport modes were calculated in addition to freight weight distance shares in order to give additional insights for more detailed transport sector modelling.
- Comparing freight weight distance, passenger weight distance and fuel use in transport, post and storage category, major differences appear for coal, LPG, fuel oil, natural gas and electricity.

Table A-5: Regional energy balance of China – final consumption in Transport

Transport sector final consumption – IEA energy balance	Transport sector final consumption – NBS provincial energy balance	Transport sector final consumption – alternative provincial data	Key Indicator – EAST CHINA	Key Indicator – CENTRAL CHINA	Key Indicator – WEST CHINA
Coal and coal products					
Hard coal: Rail	**Raw coal, washed coal, other cleaned coal, briquettes, gangue:** Transport, storage and post	Freight weight distance –rail (NBS YB); Passenger weight distance rail (NBS YB); Length of rail network (NBS YB)	**Raw coal:** Freight weight distance rail: 36% Passenger weight distance rail:40% Transport: 17%	**Raw coal:** Freight weight distance rail: 43% Passenger weight distance rail: 42% Transport: 64%	**Raw coal:** Freight weight distance rail: 21% Passenger weight distance rail: 18% Transport: 19%
n.a.	**Coke and other coking products:** Transport, storage and post		n.a.	n.a.	n.a.
n.a.	**Coke oven gas:** Transport, storage and post		n.a.	n.a.	n.a.
Oil and petroleum products					
LPG: Road	**LPG:** Transport, storage and post	Passenger weight distance road (NBS YB); Freight weight distance road (NBS YB); Length of highway network (NBS YB)	**LPG:** Freight weight distance road: 43% Passenger weight distance road: 50% Transport: 82%	**LPG:** Freight weight distance road: 44% Passenger weight distance road: 31% Transport: 15%	**LPG:** Freight weight distance road: 13% **Passenger weight distance road: 19%** Transport: 3%
Motor gasoline: Road	**Gasoline:** Transport, storage and post	Passenger weight distance road (NBS YB); Freight weight distance road (NBS YB); Ownership of private vehicles (NBS YB)	**Gasoline:** Freight weight distance road: 43% Passenger weight distance road: 50% Private vehicles: 59% Transport: 56%	**Gasoline:** Freight weight distance road: 44% Passenger weight distance road: 31% Private vehicles: 25% Transport: 27%	**Gasoline:** Freight weight distance road: 13% Passenger weight distance road: 19% Private vehicles: 16% Transport: 17%
Gas/diesel oil: Road Rail Domestic navigation Pipeline transport	**Diesel oil:** Transport, storage and post	Passenger – weight distance – road, rail, inland waterways (NBS YB); Freight – weight distance – road, rail, inland waterways (NBS YB)	**Diesel oil:** Freight weight distance road: 43% Freight weight distance rail: 36% Freight weight distance water: 92% Passenger weight distance road: 50% Passenger weight distance rail: 40% Passenger weight distance water: 61% Transport: 49%	**Diesel oil:** Freight weight distance road: 44% Freight weight distance rail: 43% Freight weight distance water: 6% Passenger weight distance road: 31% Passenger weight distance rail: 42% Passenger weight distance water: 10% Transport: 29%	**Diesel oil:** Freight weight distance road: 13% Freight weight distance rail: 21% Freight weight distance water: 2% Passenger weight distance road: 19% Passenger weight distance rail: 18% Passenger weight distance water: 29% Transport: 22%
Fuel oil: Road Rail Domestic navigation	**Fuel oil:** Transport, storage and post	Passenger – weight distance – road, rail, inland waterways (NBS YB);Freight – weight distance – road, rail, inland waterways (NBS YB)	**Fuel oil:** Freight weight distance road: 43% Freight weight distance rail: 36% Freight weight distance water: 92% Passenger weight distance road: 50% Passenger weight distance rail: 40% Passenger weight distance water: 61% Transport: 94%	**Fuel oil:** Freight weight distance road: 44% Freight weight distance rail: 43% Freight weight distance water: 6% Passenger weight distance road: 31% Passenger weight distance rail: 42% Passenger weight distance water: 10% Transport: 6%	**Fuel oil:** Freight weight distance road: 13% Freight weight distance rail: 21% Freight weight distance water: 2% Passenger weight distance road: 19% Passenger weight distance rail: 18% Passenger weight distance water: 29%
Jet fuel type kerosene: Domestic aviation	**Kerosene:** Transport, storage and post		**Kerosene:** Transport: 74%	**Kerosene:** Transport: 18%	**Kerosene:** Transport: 8%
n.a.	**Naphtha, Lubricants, Petroleum waxes, white spirits, bitumen asphalt, other petroleum products:** Transport, storage and post		n.a.	n.a.	n.a.
Natural gas					
Natural gas: Road Pipeline transport	**Natural gas, LNG:** Transport, storage and post	Freight weight distance road (NBS YB); Passenger weight distance road (NBS YB);	**Natural gas:** Freight weight distance road: 43% Passenger weight distance road: 50% Transport: 26%	**Natural gas:** Freight weight distance road: 44% Passenger weight distance road: 31% Transport:35%	**Natural gas:** Freight weight distance road: 13% Passenger weight distance road: 19% Transport: 39%
Electricity and Heat					
Electricity: Rail	**Electricity:** Transport, storage and post	Freight weight distance –rail (NBS YB); Passenger weight distance rail (NBS YB);	**Electricity:** Freight weight distance rail: 36% Passenger weight distance rail:40% Transport: 50%	**Electricity:** Freight weight distance rail: 43% Passenger weight distance rail: 42% Transport: 28%	**Electricity:** Freight weight distance rail: 21% Passenger weight distance rail: 18% Transport: 22%
n.a.	**Heat:** Transport, storage and post		n.a.	n.a.	n.a.

A.4.4.3. Commercial and public services

IEA energy balance – Commercial and public services

The commercial and public service category in IEA's energy balance specifies fuels consumed by business and offices in the public and private sectors. This category is based on UN ISIC and includes a variety of disparate activities, amongst others water supply, sewage, waste management and remediation activities; real estate activities; accommodation and food services; repair and installation of machinery and equipment; wholesale and retail trade; professional, scientific and technical activities; public administration and defence; education; healthcare; arts, entertainment and recreation; financial services.

China provincial energy balance – Commercial and public services

The main category in China's provincial energy balance that can be attributed to ISIC definition of commercial and public services is final energy consumption in "wholesale, retail trade and hotel, restaurants". A share of energy use that in IEA's energy balance format is reported under commercial and public service sector use is included in industrial consumption in China's energy balance, such as water supply, sewage, waste management; repair and installation of machinery and equipment; arts, entertainment and recreation. Furthermore some commercial and public services, such as defence, are merged in "other" end use. Research suggests that up to 44% of commercial energy consumption in China is allocated in other end use sectors when comparing Chinese and international statistics (MGI 2007).

Conclusions – Commercial and public services

Final consumption data for the service sector should be carefully analyzed, as few Chinese and alternative statistics currently focus on this segment. The NBS data for the service sector and other sector are used to derive regional shares of household fuel consumption in Table A-6 below. The sector with the largest fuel consumption is chosen to calculate regional shares.

Table A-6: Regional energy balance of China – final consumption in the Commercial / Service Sector

Commercial and public services consumption – IEA energy balance	Commercial and public services consumption – NBS provincial energy balance	Commercial and public services consumption – alternative provincial data	Key Indicator – EAST CHINA	Key Indicator – CENTRAL CHINA	Key Indicator – WEST CHINA
Coal and coal products					
Hard coal	**Raw coal, briquettes:** Wholesale, Retail Trade and Hotels, Restaurants Others		**Raw coal:** Service: 35% Other sectors: 40%	**Raw coal:** Service: 42% Other sectors: 29%	**Raw coal:** Service: 23% Other sectors: 31%
Coke	**Coke:** Wholesale, Retail Trade and Hotels, Restaurants Others		**Coke:** Service: 5% Other sectors: 100%	**Coke:** Service: 23%	**Coke:** Service: 72%
Coke oven gas	**Coke oven gas** Wholesale, Retail Trade and Hotels, Restaurants Others		**Coke oven gas:** Service: 20% Other sectors: 57%	**Coke oven gas:** Service: 52% Other sectors: 28%	**Coke oven gas:** Service: 28% Other sectors: 15%
Gas works gas	n.a.	Blast Furnace gas, Other gas	**Other coal gas:** Service: 79% Other sectors: 100%	**Other coal gas:** Service: 21%	
Oil and petroleum products					
Gas/diesel oil	**Diesel oil:** Wholesale, Retail Trade and Hotels, Restaurants Others		**Diesel oil:** Service: 45% Other sectors: 70%	**Diesel oil:** Service: 37% Other sectors: 10%	**Diesel oil:** Service: 18% Other sectors: 20%
Other kerosene	**Kerosene:** Wholesale, Retail Trade and Hotels, Restaurants Others		**Kerosene:** Service: 20% Other sectors: 13%	**Kerosene:** Service: 13% Other sectors: 64%	**Kerosene:** Service: 67% Other sectors: 23%
Fuel oil	**Fuel oil:** Wholesale, Retail Trade and Hotels, Restaurants Others		**Fuel oil:** Service: 95% Other sectors: 90%	**Fuel oil:** Service: 5% Other sectors: 10%	
n.a.	**Gasoline, white spirits, LPG, other petroleum products:** Wholesale, Retail Trade and Hotels, Restaurants Others		n.a.	n.a.	n.a.
Natural gas					
Natural gas	**Natural gas:** Wholesale, Retail Trade and Hotels, Restaurants Others		**Natural gas:** Service: 44% Other sectors: 73%	**Natural gas:** Service: 20% Other sectors: 11%	**Natural gas:** Service: 36% Other sectors: 17%
Electricity and Heat					
Electricity	**Electricity:** Wholesale, Retail Trade and Hotels, Restaurants Others		**Electricity:** Other sectors: 69% Service: 65%	**Electricity:** Other sectors: 19% Service: 22%	**Electricity:** Other sectors: 12% Service: 13%
Heat	**Heat:** Wholesale, Retail Trade and Hotels, Restaurants Others		**Heat:** Service: 67% Other sectors: 66%	**Heat:** Service: 31% Other sectors: 29%	**Heat:** Service: 2% Other sectors: 5%

A.4.4.4. Residential Sector

IEA energy balance – Residential Sector

IEA's energy balance includes consumption by households in the residential end use sector, excluding fuels used by households for transport. Biomass end use in China is mainly reported in the residential sector, as many rural household depend on biomass for final energy consumption needs.

China provincial energy balance – Residential Sector

Data for household consumption by fuel, disaggregated for urban and rural residents, are given in Chinese energy statistics by NBS. Raw coal dominates the hard coal products used in China. Briquettes and washed coal still play a minor role as Chinese statistics suggest. Contrary to international best practice, statistics on household energy use might include fuels and electricity used in housing that is operated by enterprises in industry and other sectors. Bio-energy use is furthermore excluded from NBS energy balances. Many figures for residential energy consumption are estimates informed by urban and rural surveys of limited sample size, sales reports from utilities and energy marketers, and specific reports on for instance rural energy access.

Alternative provincial data – Residential Sector

Urban residential coal use can be cross-checked through enterprises that report sales of coal briquettes. Urban residential gas and electricity use can be tracked through utilities that report gas and electricity sales. Since there are no records for a large portion of coal sales to rural households, estimates of rural residential coal use could be developed by combining information on output from small rural coal mines and survey data on coal purchases by rural households (LBNL 2001).

A few studies on population without electricity access in China's rural areas exist, which provide additional data on the use of biomass and kerosene (WB 2007). A recent ADB study summarized the status of China's central heating network and the population requiring space heating (ADB 2010).

With regards to biomass end use, the biomass projects registered in the CDM pipeline were analysed. About 10% of China's nearly 4000 CDM projects relate to biomass (UNEP 2013). The capacity and emission reduction potential from biomass use of the projects could be used as a bottom up indicator for regional biomass use in China.

Conclusions – Residential Sector

Final consumption data for rural households should be carefully analyzed, as only irregular surveys and national census data provide detailed energy statistics on this rapidly growing and changing sector. As few alternative residential energy statistics on China's provinces exist, the set of household data published in the NBS yearbook is used to derive regional shares of household fuel consumption in Table A-7 below.

Table A-7: Regional energy balance of China – final consumption in the Residential Sector

Residential consumption – IEA energy balance	Residential consumption – NBS provincial energy balance	Residential consumption – alternative provincial data	Key Indicator – EAST CHINA	Key Indicator – CENTRAL CHINA	Key Indicator – WEST CHINA
Coal and coal products					
Hard coal	**Raw coal, other washed coal and briquettes:** Urban Households Rural Households		**Raw coal:** Households: 23% Urban:27% Rural: 20%	**Raw coal:** Households: 41% Urban: 54% Rural: 34%	**Raw coal:** Households: 36% Urban: 19% Rural: 46%
Coke	**Coke:** Urban Households Rural Households		**Coke:** Households: 0% Urban: 0% Rural: 0%	**Coke:** Households: 92% Urban:95% Rural: 40%	**Coke:** Households: 8% Urban:5% Rural: 60%
Coke oven gas	**Coke oven gas:** Urban Households Rural Households		**Coke oven gas:** Households: 30% Urban: 31%	**Coke oven gas:** Households: 60% Urban:59% Rural: 100%	**Coke oven gas:** Households: 10% Urban:10%
Gas works gas	n.a.	Other gas	**Other coal gas:** Households: 97% Urban: 97%	**Other coal gas:** Households: 2% Urban:2%	**Other coal gas:** Households: 1% Urban:1%
n.a.	**Blast furnace gas, converter gas and other gas:** Urban Households		n.a.	n.a.	n.a.
Oil and petroleum products					
Gas/diesel oil	**Diesel oil:** Urban Households Rural Households		**Diesel oil:** Households: 47% Urban: 36% Rural: 61%	**Diesel oil:** Households: 48% Urban: 61% Rural: 21%	**Diesel oil:** Households: 5% Urban: 3% Rural: 18%
Other kerosene	**Kerosene:** Urban Households Rural Households	Spatial distribution of population requiring kerosene for lighting (ADB)	**Kerosene:** Households: 23% Urban: 15% Rural: 24%	**Kerosene:** Households: 61% Urban: 1% Rural: 71%	**Kerosene:** Households: 16% Urban: 84% Rural: 5% Kerosene lighting: 100%
LPG	**LPG:** Urban Households Rural Households		**LPG:** Households: 73% Urban: 70% Rural: 82%	**LPG:** Households: 22% Urban: 25% Rural: 14%	**LPG:** Households: 5% Urban: 5% Rural: 4%
n.a.	**Gasoline, fuel oil, lubricants, bitumen asphalt, other petroleum products:** Urban Households Rural Households		n.a.	n.a.	n.a.
Natural gas					
Natural gas	**Natural gas:** Urban Households Rural Households		**Natural gas:** Households: 35% Urban: 34% Rural: 70%	**Natural gas:** Households: 21% Urban: 21% Rural: 6%	**Natural gas:** Households: 44% Urban: 45% Rural: 26%
n.a.	**LNG:** Urban Households		n.a.	n.a.	n.a.
Bio-Energy					
Bio-fuels	n.a.	Emission reduction of registered biomass CDM projects (UNEP)	**Biomass CDM:** 54%	**Biomass CDM:** 37%	**Biomass CDM:** 9%
Biogas	n.a.	Biogas production for power generation (NDRC)	**Biogas:** 24%	**Biogas:** 48%	**Biogas:** 28%
Electricity and Heat					
Electricity	**Electricity:** Urban Households Rural Households	Population without electricity (WB study); Rural hydropower production small scale (NBS YB)	**Electricity:** Households: 56% Urban: 55% Rural: 58% Rural hydro: 79%	**Electricity:** Households: 27% Urban: 27% Rural: 27% Rural hydro: 13%	**Electricity:** Households: 17% Urban: 18% Rural: 15% Rural hydro: 8% No electricity: 100%
Heat	**Heat:** Urban Households Rural Households	Population requiring space heating (ADB); Central heating network length (NBS YB)	**Heat:** Households: 40% Urban: 39% Rural: 100% Space heating: 45% Heat network: 68%	**Heat:** Households: 44% Urban: 44% Space heating: 33% Heat network: 25%	**Heat:** Households: 16% Urban: 17% Space heating: 22% Heat network: 7%

A.4.4.5. Agriculture

IEA energy balance - Agriculture

Agriculture and forestry is specified as a final consumption category, apart from fishing, in the IEA energy balance.

China provincial energy balance - Agriculture

"Farming, Forestry, Animal Husbandry, Fishery Conservancy" is defined as a final energy consumption category. In Chinese statistics more fuel categories than in the IEA energy balance are used for agricultural end use, for instance natural gas and coke oven gas use is reported.

Alternative provincial data - Agriculture

Few alternative provincial statistics exists besides NBS provincial energy balances. Some NBS indicators report the distribution and use of agricultural machinery in China, including the regional distribution of diesel engines for agricultural activities, which provides an alternative estimate for diesel specific consumption in agriculture.

Conclusions - Agriculture

The fuel shares of the "Farming, Forestry, Animal Husbandry, and Fishery Conservancy" are used to calculate regional shares for East, Central and West China (see Table A-8 below). Fuels in Chinese statistics that are not represented for agricultural activities in the IEA energy balance are left out.

Table A-8: Regional energy balance of China – final consumption in Agriculture

Agriculture and forestry consumption – IEA energy balance	Agriculture consumption – NBS provincial energy balance	Agriculture consumption – alternative provincial data	Key Indicator – EAST CHINA	Key Indicator – CENTRAL CHINA	Key Indicator – WEST CHINA
Coal and coal products					
Hard coal	**Raw coal, other washed coal and briquettes**		**Raw coal:** Farming: 18%	**Raw coal:** Farming: 46%	**Raw coal:** Farming: 36%
Coke	**Coke**		n.a.	**Coke:** Farming: 49%	**Coke:** Farming: 51%
n.a.	**Coke oven gas**		n.a.	n.a.	n.a.
Oil and petroleum products					
Gas/diesel oil	**Diesel oil**	Agricultural machines with diesel engines (NBS YB)	**Diesel oil:** Farming: 48% Diesel engines: 48%	**Diesel oil:** Farming: 36% Diesel engines: 41%	**Diesel oil:** Farming: 16% Diesel engines: 11%
Motor gasoline	**Gasoline**	Agricultural machines by capacity (NBS YB)	**Gasoline:** Farming:48% Machines: 40%	**Gasoline:** Farming:41% Machines:42%	**Gasoline:** Farming:11% Machines:18%
Other kerosene	**Kerosene**		**Kerosene:** Farming: 22%	**Kerosene:** Farming: 0%	**Kerosene:** Farming: 78%
Fuel oil	**Fuel oil**		**Fuel oil:** Farming: 100%		
n.a.	**LPG, lubricants, other petroleum products**		n.a.	n.a.	n.a.
Natural gas					
n.a.	**Natural gas**		n.a.	n.a.	n.a.
Electricity and Heat					
Electricity	**Electricity**		**Electricity:** Farming: 35%	**Electricity:** Farming: 45%	**Electricity:** Farming: 20%
Heat	**Heat**		**Heat:** Farming: 0%	**Heat:** Farming: 97%	**Heat:** Farming: 3%

Acknowledgement

A part of financial support for this research is from the Sino-Danish Centre for Education and Research (SDC) (www.sinodanishcenter.dk) and the support is gratefully acknowledged. I am furthermore grateful to my colleagues at Denmark Technical University, Energy Systems Analysis Group, the members of the IEA ETSAP group, and various Chinese partners from the Chinese Academy of Sciences, the China National Renewable Energy Center and Tsinghua University for their remarks and their constructive suggestions in various meetings and seminars.

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Appendix A-1: China statistical yearbooks[10]

Table A-1.1: Macro-economic statistical yearbooks in China (including household yearbooks)

Yearbook	Publisher	Language	Frequency	Pages in recent edition	Online Bookshop Price
National Statistical Yearbook	China Statistics Press	Chinese, English	annually since 1981, English language edition annually since 1994	1096	USD 170
Statistical Yearbook for Regional Economy	China Statistics Press	Chinese, English	annually since 2000, since 2004 in a bilingual edition	567	USD 123
Customs Statistical Yearbook	China Customs Press	Chinese, English	annually since 1990, first English version in 2001	n.a.	USD 440
City Statistical Yearbook	China Statistics Press	Chinese, English	annually since 2001, first edition in 1985	401	USD 100
Input-Output Tables	China Statistics Press	Chinese	occasionally, recent editions in 2002, 2007 and 2012	493	USD 73
Rural Statistical Yearbook	China Statistics Press	Chinese	annually since 2004, first edition in 1987	n.a.	USD 82
Urban Economy Yearbook	China City Press	Chinese	occasionally, recent editions in 2010 and 2012	n.a.	USD 143
Household Survey Yearbook	China Statistics Press	Chinese	annually since 2011, combining rural and urban household data	394	USD 73
County Economic Statistical Yearbook	China Statistics Press	Chinese	annually since 2005	n.a.	USD 90

Table A-1.2: Energy specific statistical yearbooks in China

Yearbook	Publisher	Language	Frequency	Pages in recent edition	Online Bookshop Price
Energy Statistical Yearbook	China Statistics Press	Chinese, English	annually since 2004, first English edition in 2000, first edition in 1986	286	USD 98
Energy Data Book	NDRC	Chinese	annually since 2010	87	USD 90
New energy and renewable energy Yearbook	China Renewable Energy Society	Chinese	annually since 2009	n.a.	USD 104
Electric Power Yearbook	China Electric Power Press	Chinese	annually since 2001, first edition in 1993	607	USD 89
Power Industry Yearbook	China Machinery Industry Press	Chinese	annually since 2012	663	USD 90
China Low Carbon Yearbook	China Financial and Economic Publishing House	Chinese	annually since 2010	n.a.	USD 137
Electric Power Industry Statistics	China Electricity Council	Chinese	annually since 2000, first edition in 1988	n.a.	**USD 1640**
Energy Conservation and Emission reduction Development Report	China Economic Publishing House	Chinese	annually since 2011	564	USD 69

[10] research via http://www.chinabookshop.net – prices for most recent edition, if bilingual then price for English edition, n.a. = not available (assessed on August 16, 2013)

Table A-1.3: Industry specific statistical yearbooks in China

Yearbook	Publisher	Language	Frequency	Pages in recent edition	Online Bookshop Price
Chemical Industry Yearbook	China National Chemical Information Centre	Chinese, English	annually since 1984, occasional English editions since 1999	n.a.	
Steel Yearbook	China Steel Yearbook Editorial Book	Chinese, English	annually since 1992, occasional English editions since 2007, first edition in 1985	370	USD 590
Statistical Yearbook of High Technology Industry	China Statistics Press	Chinese, English	annually since 2005, bilingual editions since 2009, first edition in 2002	114	USD 87
Statistical Yearbook of the Tertiary Industry	China Statistics Press	Chinese	annually since 2006	n.a.	USD 94
Statistical Yearbook on Construction	China Statistics Press	Chinese	annually since 2000	n.a.	USD 68
Coal Industry Yearbook	Coal Information Research Centre	Chinese	annually since 2004	n.a.	USD 110
Coal Construction Yearbook	China Coal Industry Press	Chinese	occasionally, most recent edition 2006-2010	n.a.	USD 77
Coal Industry Statistics Compendium	China Coal Industry Press	Chinese	one edition for 1949-2004	n.a.	USD 90
SME Yearbook	The vast land of China Publishing House	Chinese	annually since 2006	n.a.	USD 117
Industry Economy Yearbook	China Statistics Press	Chinese	annually since 2006, first edition in 1991	455	USD 73
Industrial Economy Yearbook	China Financial and Economic Publishing House	Chinese	annually since 2005	n.a.	USD 120
Petroleum and Petrochemical Equipment Industry Yearbook	China Machinery Industry Press	Chinese	annually since 2007	n.a.	USD 90
Petrochemical Corporation Yearbook	China Petrochemical Consulting Company	Chinese	annually since 2004, first edition in 1997	n.a.	USD 87
Petroleum and Chemical Industry Statistical Yearbook	China Petroleum Group Consulting Center	Chinese	discontinued – annual editions 2001-2006	n.a.	USD 77
Machinery Industry Yearbook	China Machinery Industry Press	Chinese	annually since 2001, 1st edition in 1984	n.a.	USD 120
Nonferrous Metals Industry Yearbook	China Nonferrous Metals Industry Yearbook Editorial Board	Chinese	annually since 1998	n.a.	USD 107
China Gas Industry Yearbook	China Light Industry Press	Chinese	one edition in 2012, to be published annually	n.a.	USD 115
National Petroleum Corporation Yearbook	Petroleum Industry Press	Chinese	annually since 2004, 1st edition in 2001	n.a.	USD 89
China Iron and Steel Statistics	China Steel Industry Association	Chinese	annually since 2004, first edition in 1993	n.a.	USD 74
China Mining Yearbook	Earthquake Press	Chinese	annually since 2003, first edition in 2003	n.a.	USD 95
Steel Annual Development Report	China Steel Industry Association	Chinese	annually since 2005	n.a.	USD 90
Development Zones Yearbook	China Financial and Economic Publishing House	Chinese	annually since 2005	484	USD 107
High-tech Industrial Development Zone Yearbook	China Financial and Economic Publishing House	Chinese	annually since 2010	389	USD 76

Table A-1.4: Agriculture specific statistical yearbooks in China

Yearbook	Publisher	Language	Frequency	Pages in recent edition	Online Bookshop Price
Agriculture Yearbook	China Agriculture Press	Chinese, English	annually since 1981, English language edition annually since 1995	227	USD 180
Township Enterprises and Agricultural Product Processing Yearbook	China Agriculture Press	Chinese	annually since 2004, first edition in 1997 (as township enterprises yearbook)	505	USD 80

Table A-1.5: Transport specific statistical yearbooks in China

Yearbook	Publisher	Language	Frequency	Pages in recent edition	Online Bookshop Price
Energy-saving and new energy vehicle Yearbook	China Economic Publishing House	Chinese, English	annually since 2010, English editon in 2012	303	**USD 688**
Automotive Industry Yearbook	China Automotive Research Centre	Chinese	annually since 1993, first edition in 1991	745	USD 260
Automotive Trade Yearbook (Auto Market Almanac)	China Commercial Press (China Association of Automobile Circulation)	Chinese	annually since 1999, first edition in 1995	n.a.	USD 246
Yearbook of Transportation and Communication	Yearbook House of China Transportation and Communication	Chinese	annually since 1990, first edition in 1986	n.a.	USD 167
Statistical Yearbook of National Railway	China Railway Press	Chinese	discontinued, 2 editions for 2006 and 2007	n.a.	USD 50
Motorcycle Industry Yearbook	Motorcycle Technology Magazine	Chinese	annually since 2006	n.a.	USD 66
Civil Aviation Industry Yearbook	China Statistics Press	Chinese	annually since 2008	n.a.	USD 60

Table A-1.6: Commercial and public service specific statistical yearbooks in China

Yearbook	Publisher	Language	Frequency	Pages in recent edition	Online Bookshop Price
Urban Construction Statistical Yearbook	China Building Industry Press	Chinese, English	annually since 2003, first English edition in 2003, first edition in 2000	656	USD 98
Urban and Rural Construction Yearbook	China Building Industry Press	Chinese, English	annually since 2006 in a bilingual version	656	USD 98
Commerce Yearbook	China Business Press (Ministry of Commerce)	Chinese, English	annually since 2004 in a bilingual edition	801	USD 197
Real Estate Statistics Yearbook	China Statistics Press	Chinese	annually since 2006, first edition in 1999	n.a.	USD 123
Building Industry Yearbook	China Construction Association	Chinese	annually since 2002	n.a.	USD 104
Building Materials Industry Yearbook (Almanac)	Almanac of China Buildings Materials Industry Press	Chinese	annually since 2005, first edition in 1981	n.a.	USD 148
Chain Stores of Retail Trade and Catering Services Yearbook	China Statistics Press	Chinese	annually since 2007	n.a.	USD 103
Large-Middle Size Retail and Accomodation Enterprises Yearbook	China Statistics Press	Chinese	annually since 2007	n.a.	USD 106

Appendix A-2: Categories of a provincial energy balance in China

Table A-2.1: Categories of a provincial energy balance in China

Total Primary Energy Supply
Indigenous Production
Recovery of Energy
Moving In from Other Provinces (interprovincial import)
Import
Domestic Airplanes & Ships Refueling Abroad
Sending Out to Other Provinces (interprovincial export)
Export
Oversea Airplanes & Ships Refueling in China
Stock Change
Input & Output of Transformation
Thermal Power
Heating Supply
Coal Washing
Coking
Petroleum Refineries; including Petroleum Products input
Gas Works; including Coke input
Natural Gas Liquefaction
Briquettes
Loss
Total Final Consumption
Farming, Forestry, Animal Husbandry, Fishery Conservancy
Industry; including Non-Energy Use in Industry
Construction
Transport, Storage and Post
Wholesale, Retail Trade and Hotel, Restaurants
Others
Residential Consumption; including urban and rural consumption
Statistical Difference

Appendix A-3: Categories of a final industry consumption in the national energy balance of China

Table A-3.1: Categories of a final industry consumption in the national energy balance of China

Total Final Industry Consumption
Mining
Mining and Washing of Coal; Extraction of Petroleum and Natural Gas; Mining and Processing of Ferrous Metal Ores; Mining and Processing of Non-Ferrous Metal Ores; Mining and Processing of Non-metal Ores; Mining of Other Ores
Manufacturing
Smelting and Pressing of Ferrous Metals; Manufacture of Metal Products
Smelting and Pressing of Non-ferrous Metals
Manufacture of Non-metallic Mineral Products
Manufacture of Raw Chemical Materials and Chemical Products; Manufacture of Medicines; Manufacture of Chemical Fiber; Manufacture of Rubber; Manufacture of Plastics
Manufacture of Paper and Paper Products; Printing, Reproduction of Recording Media
Processing of Food from Agricultural Products; Manufacture of Foods; Manufacture of Beverages; Manufacture of Tobacco;
Manufacture of Textile; Manufacture of Textile Wearing Apparel, Footwear, and Caps; Manufacture of Leather, Fur, Feather and Related Products; Manufacture of Articles For Culture, Education and Sport Activity; Manufacture of Artwork and Other Manufacturing
Processing of Timber, Manufacture of Wood, Bamboo, Rattan, Palm, and Straw Products; Manufacture of Furniture
Processing of Petroleum, Coking, Processing of Nuclear Fuel
Manufacture of General Purpose Machinery; Manufacture of Special Purpose Machinery; Manufacture of Transport Equipment; Manufacture of Electrical Machinery and Equipment; Manufacture of Communication Equipment, Computers and Other Electronic Equipment; Manufacture of Measuring Instruments and Machinery for Cultural Activity and Office Work
Recycling and Disposal of Waste
Electric Power, Gas and Water Production and Supply
Production and Distribution of Electric Power and Heat Power
Production and Distribution of Gas
Production and Distribution of Water

Appendix A-4: Categories of the IEA energy balance

Table A-4.1: Categories of the IEA energy balance

Production
Imports
Exports
International Marine Bunkers (included in World Total)
International Aviation Bunkers (included in World Total)
Stock Changes
TPES – Total Primary Energy Supply
Transformation and Energy Industry Own Use
Transfers
Statistical Differences
Transformation Electricity Plants; CHP Plants; Heat Plants; Gas Works; Oil Refineries; Coal Transformation; Liquefaction Plants; Other Transformation
Energy Industry Own Use
Losses
TFC – Total Final Consumption
Industry Iron and Steel Industry; Chemical and petrochemical Industry; Non-ferrous metal Industry; Non-metallic mineral Industry; Transport equipment; Machinery; Mining and quarrying; Food and Tobacco; Paper, pulp and print; Wood and Wood Products; Construction; Textile and leather; Non-Specified
Transport Road; Rail; Domestic navigation; Domestic aviation; Pipeline transport; Non-specified
Residential
Commercial and Public Services
Agriculture / Forestry
Fishing
Non-Specified
Non-Energy Use; including petrochemical Feedstock

Appendix A-5: UN ISIC codes for economic activities in the energy sector

Table A-5.1: UN ISIC categories for economic activities in selected energy intensive industry sectors

Industry sub-sector	Economic activities based on UN ISIC
Iron and steel	Manufacture of basic iron and steel, Casting of iron and steel in foundries
chemical and petrochemical	Manufacture of basic chemicals, fertilizers, nitrogen compounds, plastics and synthetic rubber in primary forms; manufacture of other chemicals incl. pesticides and agrochemicals, paints, soap and detergents; manufacture of man-made fibres; Manufacture of pharmaceuticals and medicinal chemical and botanical production
non-ferrous metals industry	Manufacture of basic precious (such as gold, silver, platinum) and other non-ferrous metals (such as aluminium, zinc, lead, tin, magnesium); Casting of non-ferrous metals
non-metallic minerals industry	Manufacture of non-metallic mineral products including glass, cement, ceramics, concrete
paper, pulp and print industry	Manufacture of pulp, paper and paperboard; Printing and reproduction of recorded media

Modelling tools to evaluate China's future energy system – a review of the Chinese perspective

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Invited Review

ENERGY

doi:10.1016/j.energy.2014.03.019

Submitted on 17 July 2013; Accepted on 6 March 2014; Available online on 16 April 2014

Published on 1 May 2014

Abstract:

Research efforts to analyse China's future energy system increased tremendously over the past decade. One prominent research area is China's first binding CO_2 emission intensity target per unit of GDP and its impact on the country's economy and energy system. This paper compares 18 energy modelling tools from ten Chinese institutions. These models have been described in English language publications between 2005 and 2013, although not all are published in peer-reviewed journals. When comparing the results for three main energy system indicators across models, this paper finds that there are considerable ranges in the reference scenarios: (i) GDP is projected to grow by 630-840% from 2010-2050, (ii) energy demand could increase by 200-300% from 2010-2050, and (iii) CO_2 emissions could rise by 160-250% from 2010-2050. Although the access to the modelling tools and the underlying data remains challenging, this study concludes that the Chinese perspective, independently from the modelling approach and institution, suggests a rather gradual and long-term transition towards a low carbon economy in China. Few reference scenarios include an emission peak or stabilisation period before 2040. While policy scenarios frequently suggest efficiency improvements, a short-term and large-scale introduction of non-fossil power technologies is rarely recommended.

Keywords: energy-economy models, China, Chinese modelling tools, future energy system, energy systems analysis, energy planning

Highlights:

- This study reviews and compares 18 Chinese energy modelling tools.
- Beijing-based institutions are the drivers of energy model development since 2005.
- Reference scenarios show significant result ranges for energy demand and emissions.
- Most policy scenarios suggest a gradual low-carbon transition of China's economy.

Table of content:

B.1. Introduction

A clean-air, low-carbon, and green-growth debate has been emerging in China over the past decade. China announced its first binding CO_2-emission-intensity-reduction-target per unit of GDP in 2009, which has been integrated in the current 12th Five-Year-Plan (2011-2015). On the international level, China submitted an initial communication on climate change to the United Nations Framework Convention on Climate Change (UNFCCC) in 2004. After a four-year preparation, discussion and approval process within China a second official communication on climate change was released to UNFCCC in 2012 [1]. This domestic debate has been benefitting from a stronger focus on scientific development and energy-economy interactions in the main planning documents, including Five-Year-Plans, as well as an increase in research funding [2]. Environmental problems related to increased coal use, such as air pollution, are furthermore taking a stronger position on the agenda of Chinese policy makers [3].

A large number of modelling tools to evaluate China's future energy system has been developed subsequently by China's domestic research and non-university state institutions during the 11th and 12th Five Year Plan. In the past decade, Chinese energy modelling tools were mainly discussed in Chinese language in the country's domestic journals [4]. Chinese researchers and energy planners are increasingly publishing their results in English language, thus contributing with a Chinese perspective to the international debate on prospects and challenges for China's future energy system.

A growing body of knowledge for modelling tools to evaluate future pathways for China's energy system is evolving. We aim to contribute with this literature review to an improved understanding of the most recent Chinese energy modelling tools. We hope that the results of this paper will assist researchers and decision-makers in identifying suitable Chinese modelling tools and corresponding institutions for future, energy-related research and business collaborations.

This paper is structured as follows: Section 2 describes the methodological aspects used for comparing the various energy system models. Section 3 summarizes the results of the model review, relating to different structural model aspects and the comparison of modelling results. Section 4 comprises the discussion of results across models, followed by the author's conclusions in section 5. A model by model description, arranged in alphabetical order of the model's acronym, is available in the Appendix B-1.

B.2. Methodology

A three-phase literature review was carried out to focus on the growing number of modelling tools that have been developed by various Chinese institutions to evaluate China's future energy system.

A database of Chinese energy modelling tools was established in a first phase, drawing on academic journals and project based research reports in English language from 2005-2013. The review period was chosen from 2005 – 2013 in order to select the most recent modelling studies carried out under the 11th five year plan (2006-2010) and the 12th five year plan (2011-2015). In a second phase, the established model database served to systematically review and classify the identified modelling tools by their underlying model structure and to compile key results from recent modelling studies. Frequently used quantitative results indicators were identified and compared across the reference scenarios of the 18 models, based on the published information in English language. In a third phase, main quantitative policy recommendations from recent policy scenario studies were summarized and discussed, model by model, to complement the quantitative results with qualitative policy recommendations. The presentation of the 18 Chinese models follows an alphabetic order of the models' acronyms. The acronyms were created by combining the model name and the corresponding Chinese institution.

The limitations of this literature review relate to (i) the accessibility of the Chinese modelling tools and their underlying data; (ii) the presentation of the modelling results; and (iii) the geographic representation of China. The access to the modelling tools and their underlying data remains challenging. Therefore this paper intentionally avoids making any judgments about the performance, accuracy and reliability of the reviewed models. While keeping a narrow focus on Chinese energy modelling tools discussed in English language publications, this review is targeted to those models and related studies that are easily accessible within the international research community. Modelling tools and studies that are currently published in Chinese language are thus explicitly not considered. Limited details in the description of the model structure and the presentation of results in this paper relate to the limited availability of comparable, often quantitative data in the reviewed publications. We chose to focus on tools that represent China at a country scale, including possible sub-regional definitions, to allow for result comparison across models. Models focusing only on a single Chinese province or city are thus not included here.

B.3. Results

In total 18 Chinese modelling tools were included in the review. For the subsequent model review and comparison of results we introduced acronyms for each modelling tool in Table B-1.

B.3.1. Overview of modelling tools and institutions

The 18 identified modelling tools were developed by ten different Chinese institutions during the period of 2005 – 2013. Both Chinese universities and high level non-university state institutions are driving the development of energy modelling tools in China. Most of these Chinese institutions are located in Beijing, the administrative and research centre of China.

Twelve of the 18 modelling tools are developed by a Chinese university. As shown in Table 1, Tsinghua University is strongly represented with five of the 18 energy models. Three institutions associated with the Chinese Academy of Sciences (CAS) are furthermore active in energy system modelling, including the University of the Chinese Academy of Sciences and the University of Science and Technology of China. Two of the 18 modelling tools are developed by the Renmin University and one by the North China Electric Power University.

Six of the 18 modelling tools are developed by non-university related institution of the Chinese state. One of the reviewed energy models is used by the Development Research Centre of the State Council, China's highest administrative authority. Four of the reviewed modelling tools are developed by different groups within the Energy Research Institute (ERI). Another modelling tool is developed by the State Information Centre (SIC). ERI and SIC are part of the National Development and Reform Commission (NDRC), a central planning agency under the State Council.

B.3.2. Accessibility of information

International collaboration between Chinese and international institutions increased the accessibility of information about Chinese modelling tools and related studies in the past decade. A summary of various Chinese energy modelling tools was published in an EU-supported project report in 2007, most of these energy modelling tools were only discussed inside China's domestic journals [4]. International model comparison studies and research projects included frequently the IPAC-ERI model, which participated in the Intergovernmental Panel on Climate Change (IPCC) studies to model Chinese energy demand, energy production, emissions and emission reduction potentials [13], [29], [30]. The Roadmaps to Sustainable Energy Futures (RoSE) project recently published a comparison of four global models used to analyse the economic and technological implications of ambitious climate mitigation policies. In this international research collaboration the TIMES-TU model was used to evaluate China's future energy system in a global context [40].

As shown in Table 2, the publication of modelling results in peer reviewed journals is mainly driven by the different Chinese universities. All of the 12 modelling tools developed by a Chinese university published at least once in a peer reviewed scientific journal in English since 2005. Five of the modelling tools from Chinese universities took part in international research collaboration projects and published subsequently peer reviewed articles or research reports. Multiple Chinese modelling tools are however rarely compared in one study, such as done in the Asian Modelling Exercise, which included the IPAC-ERI model, the TOM-RU model and the MARKAL-TU model [13].

Non-university institutions of the Chinese state publish results from energy modelling studies almost exclusively in project reports, related policy briefs and magazines. In this context, the access to the modelling tools as well as the related model assumptions remains challenging. Multilateral organisations that are providing energy policy advice to various state institutions are a good starting point for research. The Organisation for Economic Co-Operation and Development (OECE) refers to the DCGE-SIC model in a recent OECD China energy policy study [4]. The EEM-ERI tool, one of seven models in a World Bank supported low carbon growth study program for developing countries, is described in one World Bank publication [33]. Details about the DCGE-DRC tool are available within research reports from the World Bank [36]. Renewable energy scenarios that were recently developed with the CREAM-ERI tool are currently only published in the magazine of the China National Renewable Energy Centre [37]. The 2050-Calc-ERI tool was developed in a bilateral collaboration with the British Government's Department of Energy and Climate Change. More than ten future energy scenarios for China are interactively presented in bilingual English-Chinese model website [25].

B.3.3. Model structure

<u>Bottom-up, top-down and hybrid approaches</u>

We classified the 18 reviewed models into bottom-up, top-down or hybrid tools, based on the model descriptions provided by Chinese researchers. Bottom-up models are defined by their explicit energy technology and process representation, sometimes simulation models and optimization models are distinguished as a sub-category. Top-down models are characterized by implicit energy technology representation, thereby distinguishing the subcategories of input-output (IO) and computable general equilibrium (CGE) models. Hybrid models combine top-down and bottom-up modelling approaches through hard- or soft-linking. From the 18 reviewed modelling tools eight were classified as bottom-up models and eight as top-down models, as shown in Table B-2. Among the bottom-up models, two simulation models and three optimization models were identified. Four Computable General Equilibrium (CGE) models and two Input-Output (IO) models could be classified for the group of top-down models. A hybrid modelling framework was less frequently described. Hybrid energy modelling approaches are used in a MARKAL-MACRO model linking exercise carried out by Tsinghua University [8] and the newly developed CREAM-ERI model [37]. The most prominent hybrid Chinese energy model is the IPAC-ERI tool [4], [13], [22], [26], [27], [28], [29], [30], [31].

Geographic boundaries of China

We classify China's geographic boundaries in the reviewed 18 modelling tools in three categories; namely country, region and province (see Table B-2). Twelve energy models were used to publish results for China at a country wide scale, independent from the underlying modelling approach. Regional details of China's energy system were provided by five of the 18 modelling tools, including three bottom-up models and two top-down models. The regional classification of China however differs between the models, for example two region (East, West) are described in one version of the MARKAL-TU model [9], four regions (East, Northeast, Central, West) are modelled in a version of the LEAP-TU model [6] and eight regions (Northeast, Beijing-Tianjin, Northern Coastal, Eastern Coastal, Southern Coastal, Central, Northwest, Southwest) in the MRIO-CAS model [17]. Only a few of the 18 modelling tools publish results at the level of China's provinces; namely the EEM-ERI, the DCGE-SIC and the IPAC-ERI tools.

Time resolution

With regards to the time resolution, we distinguish short-term (2010-2020), medium-term (2010-2030) and long-term (2010-2050) energy modelling studies. As shown in Table 2, seven of the 18 modelling tools, including five top-down models and two bottom-up models, use a short-term perspective until 2020. Long-term scenario studies until 2050 are carried with eight of the 18 modelling tools, among them six bottom-up models, one hybrid model and one top-down model. Only 2 models are used in a medium-term time horizon, namely the LEAP-TU model [6] and the DCGE-DRC model [35]. Information about the base year of the corresponding model, if provided, is available in the model description in Appendix B-1.

B.3.4. Main application areas

An overview of main application areas for each reviewed modelling tool is given in Table B-3. Fourteen of the 18 models were applied to analyse future cost implications of technological change and potential GDP losses under climate constraints. Three CGE models focussed on structural adjustments of China's future economy. Two top-down models studied labour impacts related to energy system changes. Five bottom-up models were applied to discuss the policy impacts on China's future energy system comprising multiple end use sectors. Eleven of the models studied options for China's future power system, highlighting the importance of the future power sector configuration for China's economy. Modelling studies dedicated to analyse key sectors of China's economy besides the power sector were rarely published in English during 2005-2013. Some scenario studies for future energy and industry related research questions are published by Tsinghua University, building on the LEAP-TU model [7] and the TIMES-TU model [39]. No dedicated studies focussing on China's residential and buildings sector as well as China's rural economy and agriculture sector could be identified.

B.3.5. Comparison of main result indicators from reference scenarios

The majority of the modelling tools reported on the following three quantitative indicators as part of the reference scenarios: Gross Domestic Product (GDP), energy demand and carbon emissions. The subsequent paragraphs compare those result indicators across models, based on available data. These quantitative results are normalized to 2010 to enable comparisons across models in the review period from 2005-2013.

Economic growth indicators

One key characteristic of many Chinese modelling tools is the use of the State Council's projections for China's future economic structure, urbanisation profile and population development. Many modelling studies modelled China's GDP growth in line with China's medium-term development policies, which amongst other aspects expect China to become a moderately developed country by 2050. For example the TEDCGE-RU model translates China's future economic structure into a GDP growth target of at least USD_{2005} 15000 per capita by 2050 [20]. Figure B-1 compares the reference-scenario GDP increase across seven of the 18 modelling tools, specifying the year of publication. The Chinese economy is expected to grow considerably, independently from the modelling approach and institution. GDP growth rates of 300-450% from 2010-2030 and 630-840% from 2010-2050 are suggested across the modelling studies. China's future economic growth assumptions tend to be higher the more recent the modelling results were published, as indicated by the comparison of MARKAL-TU results which were published in 2005 [8] and 2009 [11].

Energy demand indicators

A continuous and long term increase in energy demand is suggested in the reference scenarios, based on recent studies undertaken with 10 of the 18 reviewed models. As shown in Figure B-2, China's future short- to medium-term energy demand is expected to grow by 150-225% from 2010-2030 across the reference scenarios. A comparison between top-down and bottom-up models in this regard shows, that energy demand increases are independent from the underlying modelling methodology. For the long-term bottom-up modelling studies a slightly higher energy demand increase of up to 200-300% from 2010-2050 is suggested. This translates into an absolute energy demand in the range of 5.8–8.1 billon tons of coal equivalent in 2050 [10], [16], [19], [20], [22], [25], [31]. When comparing GDP growth with energy demand growth over time, based on our results in Figures B-1 and B-2, it is visible that a much lower increase of energy demand than for GDP is suggested across modelling studies, independently from the modelling approach, the institution and the time horizon. This might indicate that reference scenarios include considerable, large-scale changes for China's future economy and energy system, for example economy-wide efficiency improvements.

Carbon emission indicators

In nine studies China's future emissions are continuously increasing in the medium- to long-term, reaching between 9-16 $GtCO_2$ in 2050. Reference scenarios assume an increase by 150-200% from 2010-2030 and by 160-250% from 2010-2050, as shown in Figure B-3. Reference scenario emission pathways until 2050 seem to be higher for top-down models than for bottom-up models, indicating that differences in the modelling approach and underlying assumptions might affect computed CO_2 emissions. When comparing growth rates of energy demand and emissions across the models' reference scenarios, as visualised in Figure 2 and Figure 3, a slightly lower emission growth is suggested. This might indicate energy efficiency improvements in a medium- to long-term perspective. Only two modelling studies suggest an emission peak or stabilization period between 2040 and 2050 in their reference scenarios; namely the IPAC-ERI model and the TOM-RU model [21], [26], [29].

B.3.6. Review of main conclusions from policy scenarios

We complement this review of modelling tools to evaluate China's future energy system with a summary of main conclusion from the wide range of policy scenarios studied. In addition to the quantitative result indicators presented and compared before, we compile characteristic insights from the perspective of Chinese researchers, as these were formulated in the conclusion sections of journal papers and research reports. These policy conclusions are listed below in line with the models' main application areas.

Costs, economic restructuring, and labour adjustments

- A MARKAL-TU study indicates high social welfare loss and GDP loss under various carbon constraints [8].
- A TEDCGE-RU study highlights the following relationship between GDP loss and carbon policies for China: the earlier an emission constraint is implemented in China, the higher the GDP loss will be [20].
- A MESSAGE-UCAS study highlights high costs when introducing low carbon technologies at a larger scale in China [19].
- A TOM-RU study indicates high costs when shifting to a low carbon development in China, suggesting subsequently avoiding investments in low-carbon technologies in the short-term until further research is carried out [22].
- An IPAT-CUMT study suggests that emission reductions will reduce future economic growth in China [24].
- An EEM-ERI study highlighted net losses for China's coal industry under a renewable electricity generation target of 15% by 2020 [32].
- A DCGE-SIC study concludes that carbon pricing has a strong negative impact on China's energy intensive sectors: various carbon tax schemes were leading to a decline of the coal mining, petroleum industry and power generation sector [34].
- A DCGE-DRC study concluded that continuous rapid growth is possible for China with the right policy mix, including economic adjustment towards less industry and more services in a mid- and long-term perspective [35].
- The CREAM-ERI studies concludes that an ambitious renewable energy scenario, including amongst others ambitious CO_2 emission caps, a construction stop for new coal power plants after 2015, and a switch from fossil fuel to electricity in the transport and industry sectors, will result in the highest total energy system costs across the studied scenarios [37].

Energy demand, energy system impacts and power transition

- Two LEAP-TU studies conclude that coal will remain the major future energy carrier in China [6] and that nuclear and hydro power as well as demand management will play an increasing role when introducing emission reduction policies in the electricity sector [5].
- Two MARKAL-TU studies conclude that carbon capture and storage (CCS) technologies will be more promising to reduce China's CO_2 emissions until 2050 than wind and nuclear energy [10], [11].
- A PMP-TU study suggests that fossil power will dominate in China until 2050, even after the introduction of carbon pricing [14].
- An IO-TU study that suggested a net job gain from China's renewable energy policies during 2006-2010 when taking into account layoffs from the coal industry restructuring [15].
- A TIMES-TU study highlights that coal remains the major fuel in China's primary energy fuel mix, with a stabilisation of absolute coal consumption after 2030 [16].
- A POM-CUST study suggests that power technology diversifications away from coal decreases China's portfolio risk, but increases generation costs [18].
- A MESSAGE-UCAS study suggests that any future mitigation of the country's CO_2 emissions will mainly come from cleaner coal combustion and CCS [19].

- Based on China’s coal-based resource endowment, a TOM-RU study concludes that CCS technologies will be of great significance to China's climate change mitigation efforts [21].
- An EEM-ERI study suggests that mandatory renewable energy targets will challenge resource limits and regional energy disparities inside China, but will decrease air pollution [32].
- A CREAM-ERI study highlights that under ambitious renewable energy targets, the renewable energy share in primary energy demand could increase from 9% in 2010 to 56% in 2050, calculated by the standard Chinese coal-equivalent calculation methodology [37].

Emissions, natural resources and environment

- A LEAP-TU study concluded that emissions from the iron and steel industry are a key future challenge for China [7].
- A MARKAL-TU study suggested a long term perspective for China's energy system with a potential emission stabilization period between 2035-2050 after a period of growing demand from industry, transport, buildings and consumers [10].
- A TIMES-TU study concluded that the period before 2020 is very crucial to determine the future direction and level of energy demand and supply in China and highlights the need to transform economic development patterns timely to control rapid growth of final energy demand [16].
- A TEDCGE-RU study advises against an absolute emission reduction pledge of China under the Kyoto protocol [20]. This argumentation was supported by the current lack of many advanced technologies for emission control and abatement in China.
- A recent IPAC-ERI study suggested that recent and continued technological progress will make it possible for China to limit its CO_2 emissions and for these emissions to peak before 2025 [26].
- A DCGE-DRC study suggests that resources and environmental pressures will present mid- and long-term constraints to China's economic growth [36].

B.4. Discussion

This literature review of Chinese energy modelling tools discusses and compares research questions, modelling results and policy recommendation of high priority from a Chinese perspective in an international context. An increasing number of energy modelling tools is being developed by a range of university and non-university state institutions in China. Beijing based institutions are the drivers of energy model development in China. This review identified and compared 18 mathematical models from 10 different Chinese institutions. A broad range of modelling approaches is used by Chinese researchers, including bottom-up, top-down and hybrid models, with different level of detail available in corresponding publications. The majority of the Chinese modelling studies published results for China at a country wide scale in English, independent from the underlying modelling approach, allowing for interesting comparisons across models.

Access to information about the Chinese modelling tools and corresponding results is based on English-language information published from 2005-2013. Only 13 of the 18 reviewed models are however discussed in peer-reviewed journal papers. In order to provide a comprehensive overview of recent Chinese modelling tools, we partially base our results on information from research reports, which lack an independent academic peer review process. This applies mainly for some the top-down models, which are used in non-university state institutions. For some of the modelling tools reviewed, the number of international available publications since 2005 was moreover limited. The results presented here are thus depending on the review methodology; the discussed limitations could impact the level of detail provided and the comparison of results across models.

Overall, there has been a strong research focus on cost-related impacts of energy and climate policies by Chinese researchers. This is independent from the underlying modelling approach and the institution. Potential future fossil and renewable technologies for China's coal-based energy and power system were frequently analysed, in particular when using the technology-rich bottom-up models. Many of the bottom-up models studied technology changes for China's future power system, highlighting the importance of the power sector for China's economy. Applications areas that were rarely studied include China's industry or transport sector, China's residential and buildings sector as well as China's rural economy and agriculture.

Economic growth in line with the official government targets was identified as a main factor driving future energy demand and CO_2 emission increase across models. The modelling tools will likely translate China's ambitious economic growth targets into a growing energy demand, assuming increased industrial production, higher construction activity and more transportation use for China's future energy system. When comparing key energy system indicators in the reference scenarios, this study finds that there is a considerable range of results across the models. When comparing growth rates of the overall economy and energy demand across models, it was shown that energy demand is expected to grow much slower than economic growth in the reference scenarios. This might indicate that reference scenario assumptions include considerable changes in the country's future economic structure and efficiency improvements. A debate on policies and strategies to address China's growing emissions is continuing in the Chinese research community [38]. We find that emission pathways until 2050 seem to be higher for reviewed top-down models than for bottom-up models, indicating that differences in the underlying modelling approach and assumptions will affect computed CO_2 emissions. Policy scenarios modelled by Chinese researchers include a mix of policies stipulated in China's five year plans and medium-term strategies together with a wide range of potential energy and climate policy options. Examples are technology promotion measures, restructuring of economic sectors, energy or carbon taxes, emission caps, and emission intensity targets. Most of the policy scenarios are difficult to compare in quantitative terms due to different modelling approaches and underlying assumptions as well as limited accessibility of the modelling tool itself.

We find that the majority of Chinese modelling studies conclude with a cautious perspective on a low-carbon development path for China, suggesting a long-term and gradual transition towards a more sustainable, future energy system. Some of the modelling studies advised clearly against short-term emission reduction targets and emission peaks for China. Only a few studies highlight the benefits of a larger use of renewable energy sources in China's energy system. Most power sector studies suggest a more efficient use of coal, partly combined with the deployment of CCS and nuclear power generation technologies. One of the most prominent models, the IPAC-ERI tool, suggests a more aggressive low carbon energy system pathway for China. The IPAC-ERI tool includes a policy-scenario-emission-peak before 2025 in order to achieve the global 2°C target. The IPAC-ERI studies are thus among the most optimistic scenarios with regards to a future emission peak for China.

B.5. Conclusion

The results of this review provide the information necessary to assist researchers and decision-makers in identifying suitable Chinese corresponding institutions and modelling tools for a specific energy-related research area. Which model is most appropriate will be decided in large part by the specific research focus, while the modelling methodology and access to information needs to be considered. For the evaluation of appropriate technologies for cleaner fossil fuel use, energy efficiency improvements and the impacts of a variety of climate change mitigation policies, the group of bottom-up models and hybrid models can supply useful insights. When investigating the economic and welfare impacts of those policies, such as carbon tax schemes and renewable energy standards, the group of top-down models might be more appropriate. Future peer-reviewed model comparison studies, specifically targeting several of the discussed Chinese modelling tools, will likely provide further insights.

Robust, transparent and credible modelling tools to analyse China's future economy and energy system will play a key role in informing decision makers about a range of energy and climate policy impacts. As China's integration in global energy markets continues, an improved understanding of China's future energy system will likely remain a priority research area for both Chinese and international researchers. While China's economy continues to expand at a faster pace than most so-called industrialised economies, a higher level of uncertainty will remain when studying energy, economic and environmental policy impacts for China. It will thus remain necessary to continuously adjust and update the modelling methodologies, technology representations and main underlying drivers of the discussed modelling tools in order to draw informed policy conclusions. Increased collaboration between Chinese and international researchers might further improve access to information and common understanding of the results from the reviewed energy modelling tools. We suggest an improved standardisation with regards to model descriptions and results presentations for any future research in this area.

Acknowledgements

Financial support for this research from the Sino-Danish Centre for Education and Research (www.sinodanishcenter.dk) is gratefully acknowledged. We are furthermore grateful to our colleagues at the Technical University of Denmark, Energy Systems Analysis Group, and the members of the International Energy Agency's ETSAP forum (www.iea-etsap.org) for their constructive suggestions. Last but not least, we would like to thank all Chinese colleagues from the Chinese Academy of Sciences, the Energy Research Institute, and Tsinghua University, who made themselves available for discussing our work in Beijing.

Appendix B.1: Modelling tools to evaluate China's future energy system

2050-Calc-ERI: China 2050 Calculator, Energy Research Institute

The Energy Research Institute's China 2050 Calculator is a bottom-up, technical energy system simulation tool, that has been developed in cooperation with the UK's Department of Energy and Climate Change. The model structure builds on the UK's 2050 energy and emission pathways calculator [25]. In consultation with numerous Chinese ministries and commissions, country specific data and assumptions were provided to build the model. The simulation period extends from 2010 to 2050, in annual steps. Four core sectors of China's energy system that are represented: the industry, the transport, the building and the residential sector. A number of sub-sectors can be tracked for every core sector, for example heavy, strategic and light industry as part of the industry sector as well as international or domestic passenger and freight transport as part of the transport sector. More than 10 conventional and unconventional fossil fuels are represented, including coal, oil, gas, coal-based methane, and shale gas. With regards to renewable sources, hydropower onshore-and offshore wind,solar PV, solar thermal, ocean energy, geothermal energy and bioenergy are modelled. Nuclear power and carbon capture and storage options are represented. The overall aim of the model is to highlight risks and trade-offs associated with future, long term energy scenarios for China. The model's energy and emission pathway scenarios are published on an interactive, bilingual English-Chinese website [25].

CGE-NCEPU: Computable General Equilibrium Model, North China Electric Power University

The North China Electric Power University established a computable general equilibrium (CGE) model in order to analyse power sector policies and reforms in China. The model's underlying equations are based on the constant-elasticity-of-substitution (CES) of imports and domestic goods supplied to China's market. The country's economy is represented by 17 sectors. The model database builds on China's 2007 input-output table and various statistical yearbooks from the country's national bureau of statistics [23]. Some modelling parameters are based on expert assumptions and data available from international literature reviews. The model was used to simulate the impact of electricity price adjustment on China's future electricity demand. In this regard, recommendations for electricity price reforms were made [4].

CREAM-ERI: China Renewable Energy Analysis Model, Energy Research Institute

The China Renewable Energy Analysis Model (CREAM) was developed by the China National Renewable Energy Centre (CNREC), a renewable energy think tank of the Energy Research Institute. The model development benefited from collaborations between CNREC, the US National Renewable Energy Centre (NREL), the Danish Energy Agency (DEA) and the Japanese National Institute for Environmental Studies (NIES). Experiences from the REEDS and Balmorel models were thus incorporated into CREAM [37]. This hybrid modelling tool consists of four, soft-linked sub-models: (i) CREAM-DEMAND – a spreadsheet based model of the future energy demand in China's industry, housing and transport sector; (ii) CREAM-EDO - a bottom-up, optimization, mixed integer linear programming model of China's heat and power sector; (iii) CREAM-CGE – a China specific macro-economic model; and (iv) CREAM-TECH - a renewable and fossil-fuel based technology comparison tool. The model's core part consists of the CREAM-EDO sub-module, which allows calculating a least-cost, optimal dispatch of China's heat and power plants [37]. Various resource availability and electricity transmission capacity constraints can be modelled in hourly time steps. The model structure comprises the whole energy system of China, representing industry, transport and buildings besides the power sector. The model's database includes China's existing and planned power and heat plants on a provincial level. Cost estimates are based on IEA assumptions for oil and natural gas as well as Chinese data sources for coal and bio-energy. This model has been used to study long-term scenarios with high shares of renewable energies until 2050. The balancing of the electricity system, the flexible dispatch of power plants and interconnectors, and investments in transmission capacity were explicitly studied [37].

DCGE-SIC: Dynamic Computable General Equilibrium Model, State Information Centre

The State Information Centre of China (SIC), a think tank affiliated with the National Development and Reform Commission, has developed a large-scale, dynamic, computable general equilibrium model of the Chinese economy in collaboration with the Monash University of Australia [4]. The model development benefitted from the Monash University's modelling tools for the Australian economy [34]. The model builds on a nested, constant-elasticity-of substitution (CES) function, which allows for substitution among labour, capital, energy and land. Three dynamic mechanisms are possible: capital accumulation, liability accumulation and lagged wage rate adjustment processes. Primary energy is supplied as either coal or a hybrid of oil and gas [34]. The model's database relies on the 2007 input-output table of the Chinese economy, featuring 137 production sectors in an extended version and 34 sectors in a simplified version. Within China 30 different provinces can be modelled separately. A recent research project on energy models in China concluded that the model is able to consider emission from fossil fuel combustion, while emissions from industrial processes and non-industrial sources are lacking [4]. This model was used to study trade policies and the effects of carbon pricing on China's economy, in collaboration with the Organisation of Economic Development (OECD) [4].

EEM-ERI: Economic Evaluation Model, Energy Research Institute

The Economic Evaluation Model (EEM) of the Energy Research Institute (ERI) is a bottom-up model of China's power sector. The model has been developed since 2002 as part of the China Renewable Energy Scale-Up Program (CRESP) in collaboration with the World Bank Group. The model includes China's short- and medium-term power sector development plans on a project by project basis. About 1900 future power sector investment projects in all of China's provinces are included [32]. The model's time resolution extends from 2000 to 2020, in annual steps. A core model feature is the calculation of external costs within the country's power sector. Thus the costs of coal-based power generation can include both social and environmental damage and the investment, operation and maintenance costs. The model was used to analyse the renewable energy's share of grid power in China. Policy recommendations from the model assisted in defining the appropriate level of financial support mechanisms for renewables. The modelling methodology was furthermore used in related renewable energy investment projects with World Bank Group involvement in Croatia, South Africa and Serbia [33].

IO-TU: Input Output Model, Tsinghua University

An input-output (IO) model has been developed by China's Tsinghua University in collaboration with the State Key Joint Laboratory of Environment Simulation and Pollution Control and the country's National Energy Administration (NEA) [15]. The model is based on the Chinese 2005 input-output table, which includes 42 sectors of the country's economy. The power sector is a core part of the model, it is disaggregated in the following nine sub-sectors: small coal-fired, large coal-fired, oil, gas, hydro, nuclear, wind, biomass, and solar PV generation. China's national and provincial energy statistics as well as data from numerous power project reports build the model's data base. The model was used to analyse the direct and indirect employment impacts within a future green economy. The emission reduction measures from China's 11th Five Year Plan were considered for this study, mobility barriers or income induced employment impacts were however neglected [15].

IPAC-ERI: Integrated Policy Assessment Model for China, Energy Research Institute

The Integrated Policy Assessment Model for China (IPAC) can be classified as a hybrid modelling tool, as it is combining both top-down and bottom-up modelling approaches for China. The model is developed by the Energy Research Institute since the early 1990s in collaboration with many international research groups [4].

Over time the IPAC modelling framework expanded significantly in its scope and complexity, including to date more than 400 energy system technologies [28].

The IPAC model framework allows analysing core sectors of China's energy system over a long-term time horizon until 2100. The future model assumptions draw on GDP, population and urbanisation growth rates consistent with official government targets. The model consists of four core sub-modules: (i) the IPAC-SGM module, which mainly analyses the demand and supply and determines the energy prices based on a macro-economic partial equilibrium model approach; (ii) the IPAC-AIM/technology model, which analyses the short and mid-term energy utilization technologies under different constraints; (iii) the IPAC land use module, which analyses the emissions from land use processes such as agricultural food supplies, stock raising, forest management and biomass energy production; and (iv) the IPAC-Emission module, which mainly analyses the emissions from industrial productions [31]. The IPAC-AIM/technology sub-module is used to determine a least-cost technology mix to meet a given energy service demand. The hybrid model framework allows providing feedback endogenously, for example the energy demand derived in the energy technology module could modify the energy demand in the society, economy and energy activities module. The model has been frequently applied to provide detailed projections for China's future energy demand and related emissions [13], [22], [26], [27], [29], [30].

IPAT-CUMT: IPAT Model, China University of Mining and Technology

The IPAT model is a top-down model that has been developed by the China University of Mining and Technology in Xuzhou in cooperation with the Xuzhou Normal University. The model's set of functions describes an environmental impact (I) based on population (P), per-capita economic growth (A) and environmental load of economic growth (T), building on Ehrlich and Holdrens' economic theory from 1971 [24]. Exogenous inputs to the model are economic and population growth, primary energy demand, and a set of available technologies. Scenario assumptions were provided amongst others by the Chinese Academy of Science's group for Sustainable Development. The power sector can be represented by coal, oil, gas and non-fossil energies. This model was used to analyse China's future primary energy demand and resulting carbon dioxide emissions from 2010 to 2020, on an annual basis.

LEAP-TU: Long-range Energy Alternatives Planning Model, Tsinghua University

The Long-range Energy Alternatives Planning (LEAP) model is an integrated energy-environment and scenario-based accounting model, which is used for power sector planning in many countries worldwide. Several versions of LEAP have been developed by Tsinghua University since 2007 [4]. The model was expanded from a limited power sector focus [5] to an energy system focus including industry, commerce, transport, households and agriculture besides the power sector [6]. Modelled energy commodities include coal, coke, peat, crude oil, petroleum products, natural gas, electricity, heat, and biomass. The model is driven by energy demand and population growth projections from official Chinese government sources. The model's database draws furthermore on China's various statistical yearbooks and expert assumptions. The model is used to study a range of energy security, climate change, and low-carbon development policies until 2030.

MARKAL-TU: Market Allocation Model, Tsinghua University

The Market Allocation (MARKAL) model is a dynamic, bottom-up, technology-rich optimization model used for integrated energy, environmental and economic policy analysis in many countries worldwide. A MARKAL China model family has been developed since the late 1990s with support from US research institutes [4], [12]. Currently China specific MARKAL, MARKAL-ED (including an elastic demand feature to introduce consumers' behaviour response [10]), and MARKAL-MACRO versions (including feedback between energy demands and prices [8]) were developed by Tsinghua University. In general, the China MARKAL model family incorporates a broad range of energy exploitation, conversion, transmission, distribution and end-use processes for various energy system sectors, namely industry, transport, households, agriculture and services. A wide range of conventional fossil fuels (such as coal, oil, natural gas, coal gas), nuclear, and renewable energy sources (including hydro, wind, solar, geothermal) and some synthetic fuels (such as hydrogen and methanol) can be tracked. This model usually uses 5-year intervals over a long-term time horizon until 2050 for simulations. Energy service demands are provided exogenously, for example based on China's historical data or data from OECD countries with historic per-capita GDP indicators similar to those for China. The model is used to determine the least-cost mix of technologies and fuels to meet the country's predicted energy service demands. MARKAL China model versions also participated in recent international model comparison studies, such as the Asia Modelling Exercise [13].

MESSAGE-UCAS: Model for Energy Supply Strategy Alternatives and their General Environmental Impact, University of the Chinese Academy of Sciences

The Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) is a widely used global bottom-up, system engineering flow-optimization model. A China specific MESSAGE version was developed by the University of the Chinese Academy of Sciences (UCAS), building on the global model structure and database. By reviewing and updating global modal assumptions with regards to China specific parameters, power generation data, cost curves and other key parameters were recalibrated. Exogenous economic drivers until 2050 were provided from a modelling tool of the Energy Research Institute. The model's power sector technologies include traditional and advanced fossil-fuel-based power generation technologies and renewable ones. Ten energy commodities are tracked: coal, oil, natural gas, hydropower, solar thermal use, solar PV, wind power, biomass, nuclear, and synthetic liquid fuels. This model was used to analyse new power generation technology options for China under a greenhouse gases mitigation scenarios [19].

MRIO-CAS: Multi-Regional Input Output Model, Chinese Academy of Sciences

The multi-regional input-output (MRIO) model is a top-down model developed by several institutes of the Chinese Academy of Sciences (CAS) [4]. This model build's on Leontief's analytical framework, which is extended to encompass a multi-region modelling methodology for China. The model aims to assess the monetary interactions between four different economic sectors (agriculture, manufacturing, construction and service). Future energy demands in eight different regions in China from 2010 to 2020 can be analysed. The model's database draws on various economic, population, energy and urbanisation-related statistics and projections from official Chinese government institutions, such as the National Bureau of Statistics (NBS) [17]. The 2007 model version builds on China's 1997 MRIO table and corresponding provincial data. Economic growth is exogenously provided, based on research from the State Council's Development Research Centre [17]. Future regional GDP shares are provided from a NBS working group. Energy commodities captured are limited to primary energies (coal, natural gas and crude oil) due to the underlying input output relationship of the covered sectors.

MSCGE-DRC: Multi-Sector Computable General Equilibrium Model, Development Research Centre of the State Council

The Development Research Centre (DRC) of the State Council, China's chief administrative authority, has developed a multi-sector top-down CGE model to study future trends of China's economy, industry structure and associated environmental impacts [4]. The model in its 2004 edition included 34 production sectors, later the number of covered production sectors expanded to 42 in the model's 2012 edition [36]. Fourteen representative household types can be distinguished by geographic area and income level. Four primary production factors are modelled: capital, agricultural labour, productive workers and professionals [35]. All sectors are assumed to operate under constant returns to scale and cost optimisation. The model builds on a nested, constant-elasticity-of-substitution (CES) function and assumes a recursive, dynamic structure about prices and quantities. The model is calibrated to the most recent Social Accounting Matrix (SAM) that is derived from the national input-output table. The economic growth rate and composition of population, GDP growth, supply of labour and productivity are exogenous. The rest of the world is assumed to supply imports to and demands exports from China. Investment is endogenously modelled, at a level required to achieve the targeted GDP growth. The model is frequently used in China specific research collaboration reports with the World Bank. In this context, the impacts of different pathways of growth on the country's production, demand, employment and income distribution are analysed [36]. The model was furthermore used to project scenarios for China's future economic growth under the 12th Five Year Plan [36].

PMP-TU: Power Mix Planning Model, Tsinghua University

The power mix planning model is a bottom-up optimization model of China's power sector. This model has been developed by Tsinghua University with initial support from British Petroleum [14]. The model's underlying objective function minimizes the accumulated total power system cost over the planning horizon, while satisfying a set of exogenously provided power and climate policies. Technical and economic specifications of China's power plant technologies are supplied from the China Electricity Council [14]. Scenarios for China's future power demand are provided exogenously from the Energy Research Institute. Ten types of power generation technologies are modelled, including four different coal combustion technologies, natural gas combined cycle, nuclear, wind, biomass and solar PV. The model was used to identify the optimal power technology mix for China between 2010 and 2050 [14].

POM-USTC: Portfolio Optimization Model, University of Science and Technology of China

The portfolio optimization model (POM) is a top-down model, that builds on Markowitz's pareto-optimal portfolio theory [18]. The University of Science and Technology of China has been developing this model for power sector studies in cooperation with the Chinese Academy of Sciences. Coal, nuclear, wind, and natural gas technologies are represented. Each of these technologies is characterized by a costs and a level of cost risk for power generation. The model's simulation period extends until 2020. Major exogenous assumptions include that China's economy will keep growing without any severe recession and that the country's electricity demand will increase steadily. Fuel price development projections were based on China's historic fuel prices. Risk-return relationships for various power generation portfolios in the presence of different energy policy instruments were studied [18].

TEDCGE-RU: Technology oriented dynamic Computable General Equilibrium Model, Renmin University

The Renmin University has developed a technology-oriented, dynamic, computable general equilibrium (TDCGE) model [4]. This CGE model builds on a nesting constant-elasticity-of-substitution (CES) production function. A particular feature of the model is the incorporation of endogenous technological change. Knowledge capital is part of the nesting CES structure and can substitute other input factors. The economic growth function in the model is thus driven by the endogenous accumulation of both physical and knowledge capitals an exogenous increase in the supply of labours. China’s economy is described in 41 sectors, including agriculture, mining, manufacturing (mainly industry), services and the power sector [20]. Fossil fuel and low carbon power technologies are included. The model's social accounting matrix (SAM) table was based on the Chinese Input–Output table of 2005. Exogenous data inputs include energy consumption, export demands, import supplies, substitution elasticity parameters and CO_2 emissions [20]. The simulation period, based on a recursive dynamic mechanism, extends from 2005 until 2050. This model was used to analyse the economic impact of China's climate change mitigation commitments in a global context, including the potential role of technological change in the formulation of China's national targets [20].

TIMES-TU: The Integrated MARKAL-EFOM System, Tsinghua University

The Integrated MARKAL-EFOM System (TIMES) builds on a collaborative effort under the International Energy Agency's Energy Technology Systems Analysis Programme (ETSAP). Numerous TIMES models were developed at a national and global scale. All TIMES models are bottom-up optimization models that result in an optimal reference energy system by selecting energy processes from a large set of options under imposed policy and physical constraints [12]. A China specific TIMES model is being recently developed by Tsinghua University [16]. This TIMES-TU model describes China's total energy system, comprising the agriculture, industry, transportation, commerce and residential sectors. The TIMES-TU model was combined with a domestic energy service demand projection model to derive China's future energy demand until 2050 for each end use sector to serve as model drivers. The model's underlying database and scenario assumptions include targets from a wide range of China's energy and economic policies. One recent application of the model targeted the future development of China's iron and steel industry [39]. This model was also represented in the Roadmaps to Sustainable Energy Futures project, a scenario-based analysis of low carbon economies using global and national integrated assessment models [40].

TOM-RU: Technological Optimization Model, Renmin University

The Renmin University, under its Programme of Energy and Climate Economics, has been developing a technological optimization model (TOM) to study options for a future low carbon economy and society in China [4]. This model can be classified as a bottom-up, non-linear optimization model that determines the most cost efficient technology choice for China's energy system under a series of constraints. The following four core sectors of China's energy system are modelled: power, industry (iron and steel, cement), transport, buildings. The model's database and underlying scenario assumptions draw on a wide range of China's socio-economic targets. These comprise GDP growth and composition, urbanisation progress, population growth, energy system strategies and policies, energy resource endowment and energy supply options. Technology costs include investment and operation related costs. The model participated in one large international energy model comparison, the Asia Modelling Exercise [13]. The model was furthermore representing China in a Tsinghua University led carbon-emission-scenario-comparison [22] and in socio-economic and technical studies for UNDP's China Human Development Report 2009 [21]. In this context, a variety of energy policy instruments as well as greenhouse-gas and other pollutant emissions were analysed.

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Tables

Table B-1: Overview of modelling tools and institutions

Acronym	Modelling tool	Institution	References
2050-Calc-ERI	China 2050 Calculator	Energy Research Institute	[25]
CGE-NCEPU	Computable General Equilibrium Model	North China Electric Power University	[4], [23]
CREAM-ERI	China Renewable Energy Analyses Model	Energy Research Institute	[37]
DCGE-SIC	Dynamic Computable General Equilibrium Model	State Information Centre	[2], [4], [34]
EEM-ERI	Economic Evaluation Model	Energy Research Institute	[32], [33]
IO-TU	Input Output Model	Tsinghua University	[15]
IPAC-ERI	Integrated Policy Assessment Model for China	Energy Research Institute	[4], [13], [22], [26], [27], [28], [29], [30], [31]
IPAT-CUMT	IPAT Model	China University of Mining and Technology	[24]
LEAP-TU	Long-range Energy Alternatives Planning Model	Tsinghua University	[4], [5], [6], [7]
MARKAL-TU	Market Allocation Model	Tsinghua University	[4], [8], [9], [10], [11], [12], [13]
MESSAGE-UCAS	Model for Energy Supply Strategy Alternatives and their General Environmental Impact	University of the Chinese Academy of Sciences	[19]
MRIO-CAS	Multi-Regional Input Output Model	Chinese Academy of Sciences	[4], [17]
MSCGE-DRC	Multi-Sector Computable General Equilibrium Model	Development Research Centre, State Council	[4], [35], [36]
PMP-TU	Power Mix Planning Model	Tsinghua University	[14]
POM-USTC	Portfolio optimization Model	University of Science and Technology of China	[18]
TEDCGE-RU	Technology oriented dynamic Computable General Equilibrium Model	Renmin University of China	[4], [20]
TIMES-TU	The Integrated MARKAL-EFOM System	Tsinghua University	[16], [39], [40]
TOM-RU	Technological Optimization Model	Renmin University of China	[21], [22]

Table B-2: Comparison of modelling approaches and access to information

Modelling tool (acronym)	Institution		Access to information			Modelling approach							Geographic boundaries			Time resolution		
	University	Non-University, State	Peer reviewed journal	Project report	Model website	Bottom Up – Simulation	Bottom Up – Optimization	Bottom Up – no further details	Hybrid	Top Down – Input Output	Top Down – CGE	Top Down – no further details	Country	Region	Province	Short term	Medium term	Long term
2050-Calc-ERI		√			√	√							√					√
CGE-NCEPU	√		√								√		√			√		
CREAM-ERI		√		√					√					√				√
DCGE-SIC		√		√							√				√	√		
EEM-ERI		√		√				√							√	√		
IO-TU	√		√							√			√			√		
IPAC-ERI		√	√	√					√				√	√	√			√
IPAT-CUMT	√		√									√	√			√		
LEAP-TU	√		√	√		√								√			√	
MARKAL-TU	√		√	√			√							√				√
MESSAGE-UCAS	√		√				√						√					√
MRIO-CAS	√		√	√						√				√		√		
MSCGE-DRC		√		√							√		√				√	
PMP-TU	√		√					√					√					√
POM-USTC	√		√									√	√			√		
TEDCGE-RU	√		√	√							√		√					√
TIMES-TU	√		√				√						√					√
TOM-RU	√		√	√				√					√					√

Table B-3: Comparison of main application areas – policy scenarios

Modelling tool - Acronym	Economic and System Costs	Economic Re-structuring	Labour Adjustments	Impact on Energy Demand	Comparison of multiple end use Sectors	Power System Transition	Emissions, Natural Resources and Environment
2050-Calc-ERI				√	√		√
CGE-NCEPU	√	√		√		√	
CREAM-ERI	√	√		√	√	√	√
DCGE-SIC	√	√	√				√
EEM-ERI	√					√	
IO-TU	√		√				
IPAC-ERI	√	√		√	√	√	√
IPAT-CUMT	√			√			√
LEAP-TU	√			√	√	√	√
MARKAL-TU	√			√	√	√	√
MESSAGE-UCAS	√				√	√	√
MRIO-CAS				√			√
MSCGE-DRC	√	√					
PMP-TU				√		√	
POM-USTC	√					√	
TEDCGE-RU	√						√
TIMES-TU	√			√	√	√	√
TOM-RU	√					√	√

Figures

Figure B-1: Comparison of China's future GDP growth – reference scenarios

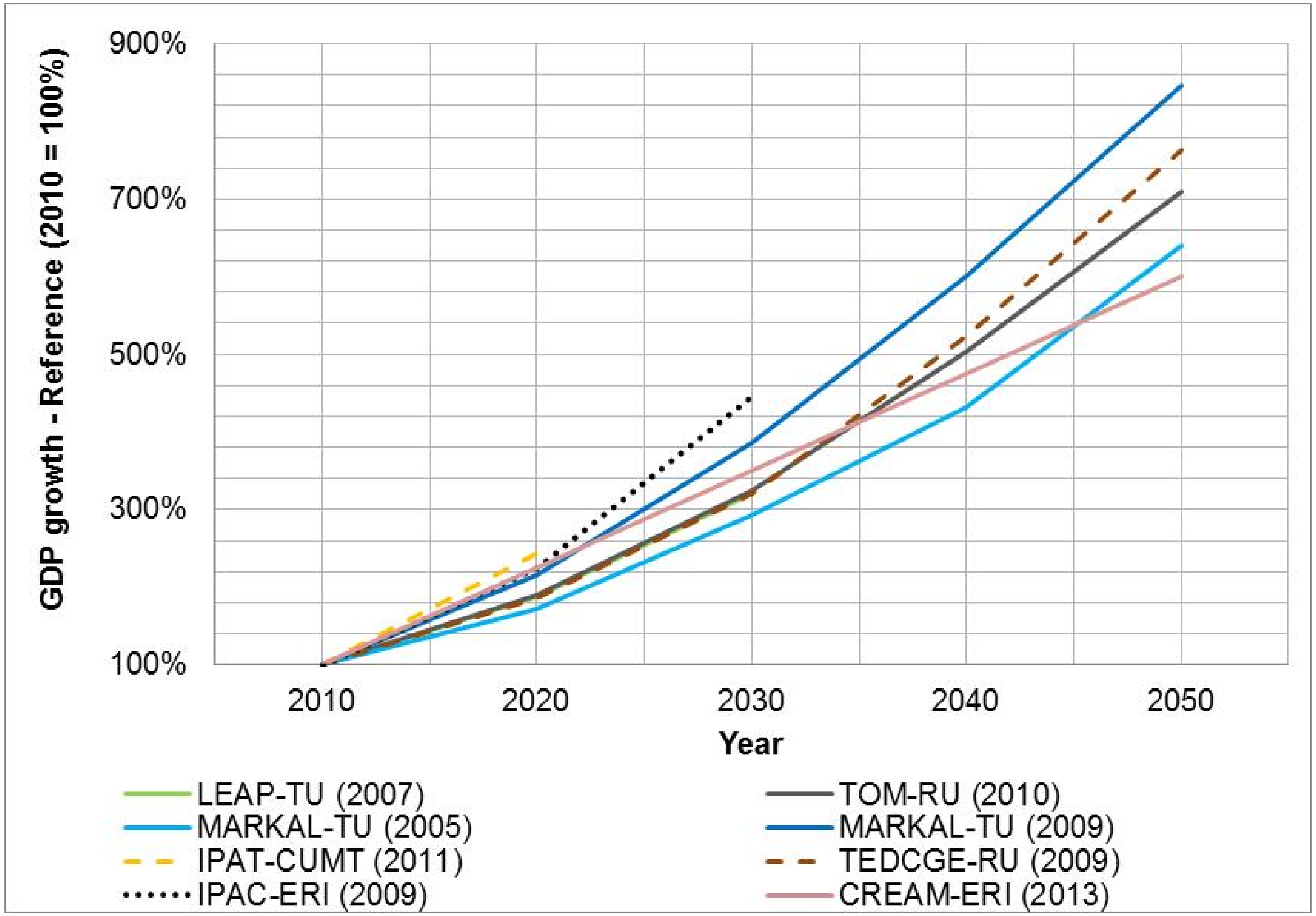


Figure B-2: Comparison of China's future energy demand – reference scenarios

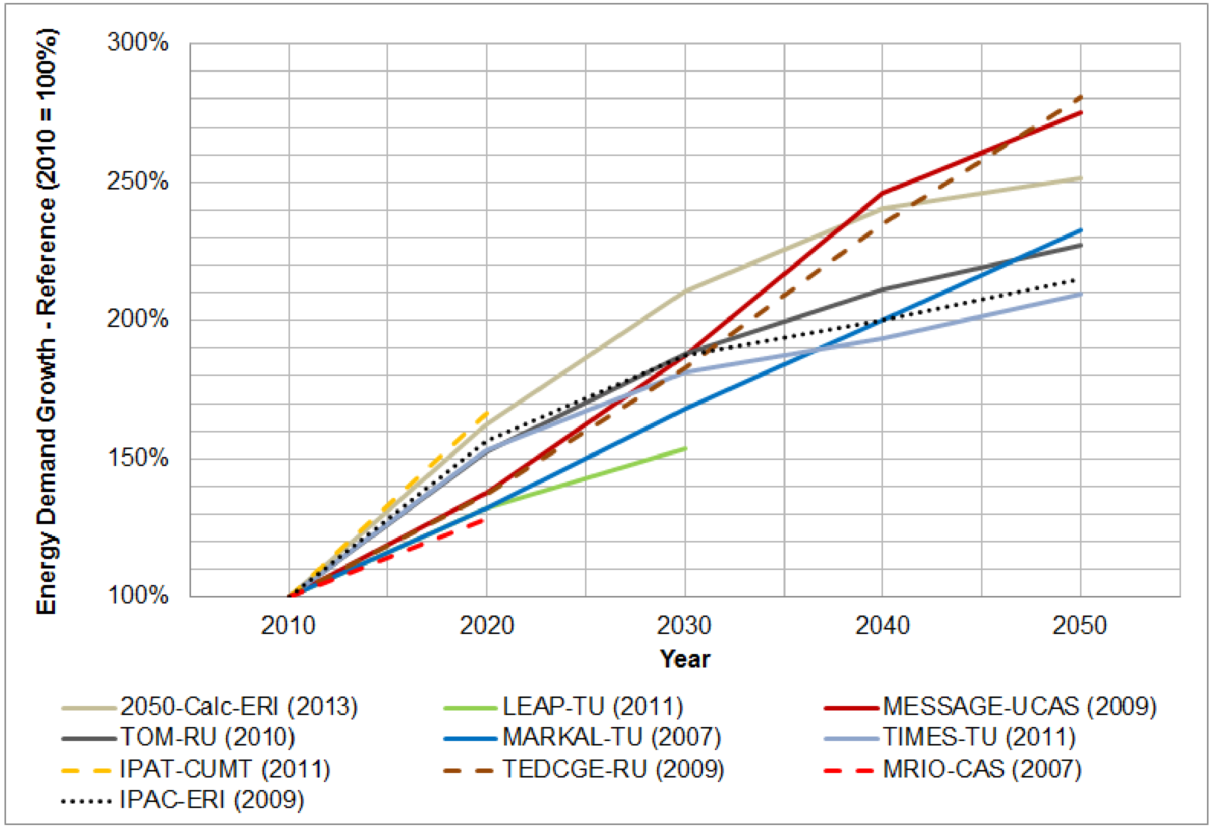
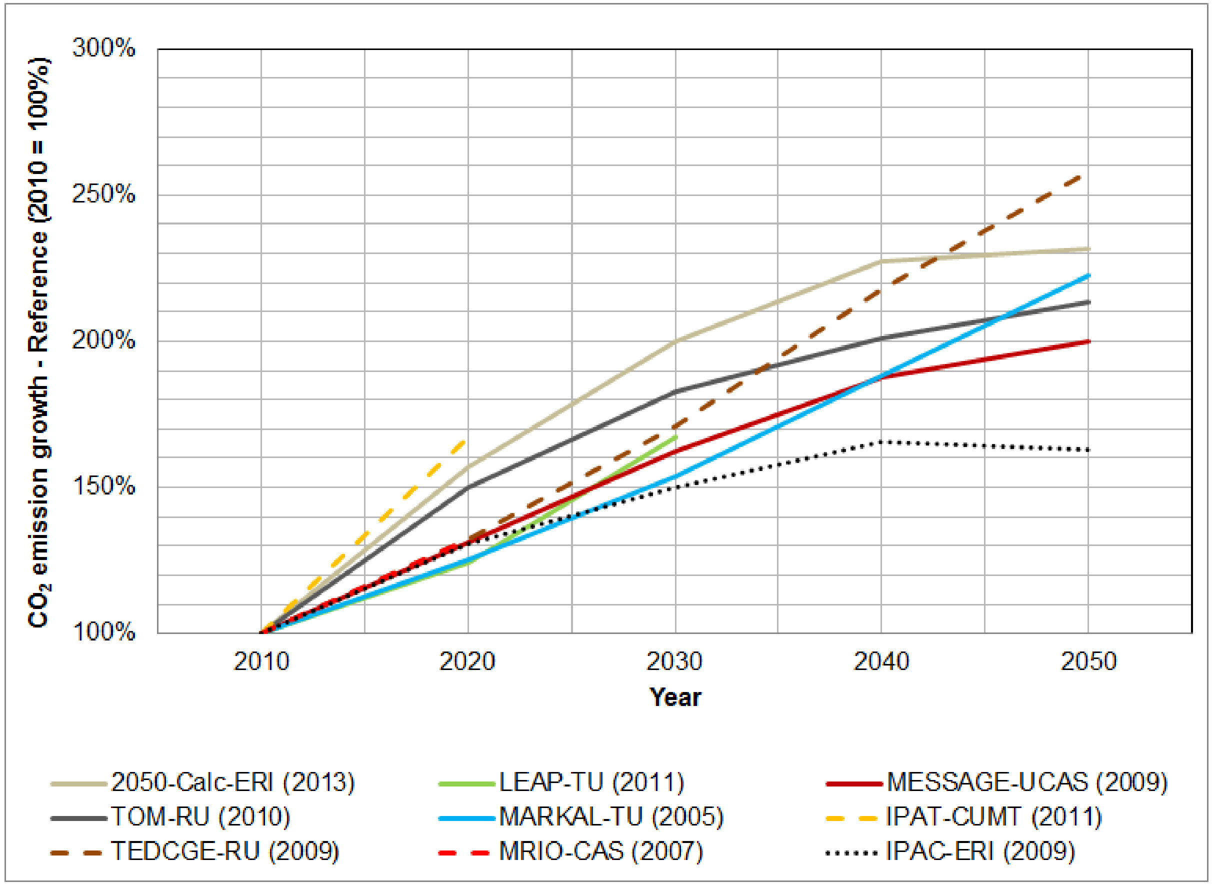


Figure B-3: Comparison of China's future CO_2 emissions – reference scenarios



Mapping and benchmarking regional disparities in China's energy supply, transformation, and end-use in 2010

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Journal Article

APPLIED ENERGY

Submitted 21 March 2014; Revised 08 December 2014; Accepted 03 January 2015;

Available online 04 2015 in

doi:10.1016/j.apenergy.2015.01.011

Abstract:

China's past economic development policies resulted in different energy infrastructure patterns across China. Regional disparities in China's current energy flow patterns are rarely visualised and quantified from a comprehensive, system-wide perspective. This study constructs Sankey diagrams for three regions of China and quantifies the following major regional disparities: (i) West-China and Central-China accounts for about 89% of the national domestic coal production. (ii) About 50% of coal fired power generation and 90% of refining can be mapped to East-China. (iii) East-China also dominated industrial energy consumption in 2010, accounting for about 70% of national oil/petroleum product use, about 58% of coal use and about 53% of electricity use. This paper highlights the need to combine national and regionally energy planning in order to account for the spatial heterogeneity in China's energy infrastructure, such as future West-China development strategies and future regional energy intensity targets and corresponding CO_2 emission mitigation measures. More comparable and transparent research is needed to better understand and assess China’s provincial and national energy data, in particular for coal-related statistics. We find data differences of up to 46% for coal, which can be caused by statistical inconsistencies and assumptions in our methodology.

Keywords: China, Sankey diagram, energy flow, regional disparities, energy balance, energy statistics

Highlights:

- West-China and Central-China produced 89% of China's coal in 2010.
- About 50% of coal fired power generation and 90% of refining is in East-China.
- East-China's industry consumes about 70% of oil; 58% of coal and 53% of electricity.
- Inconsistencies in China's national and provincial statistics in 2010 are huge, in particular for coal.

Table of content:

C.1. Introduction

China is the world's largest energy consumer and energy sector decisions in China have global implications [Howarth et al, 2014]. China's past economic development policies resulted in a large degree of regional disparity. China's successful economic development policies, which were laid out in the 7th five year plan (1986-1990), targeted different regional patterns of industrialisation and production for East-, Central-, and West-China [NPC, 1985]. The coastal provinces of China have been in the focus of China's economic development policies since many years, amongst others due to their favourable geographic location for international trade and foreign investments [Keidel, 2009], [Zhang, 2001]. China's past economic development policies resulted subsequently in different energy infrastructure investments across China. China's current energy infrastructure is thus showing different regional characteristics in energy supply, transformation, and end-use, such as in the status of energy transmission/distribution systems and the location of major load centres.

Many China-focussed research areas are in the process of switching from national level to regional and provincial level analysis, in order to get a more detailed picture of China and provide better targeted policy recommendations. China-specific research at a sub-national level highlights large disparities between the highly developed coastal provinces and other provinces in the central and western regions of China. Chinese rural income and household consumption disparities have increased within China since the past 20 years [Keidel, 2009]. Regional disparities in China's energy system are being analysed more frequently in recent years, as the following examples show: Regional inequity in CO_2 emissions and emission leakage within China is considerable and requires regional oriented policy instruments [Dong and Liang, 2014]. About 57% of China's emissions are related to goods that are consumed outside of the province where they are produced [Feng, 2013]. Jiangsu province, one of the highly developed coastal provinces, relied in 2009 about 91% on energy imports from other provinces of China or foreign countries [Zhang, 2012]. China's provincial and national energy productivity potentials and energy efficiency targets vary across China's provinces, suggesting more targeted research and sharing of best practises with other countries [Howarth at al., 2014].

To the best of our knowledge, there is currently no regional energy flow analysis for China available, which calculates and visualises regional disparities in China's energy system from a national and a regional system perspective. Such an analysis would require accounting for all major fuels and energy carriers in energy supply, energy transformation, and end-use. While national level energy flow charts for China are being used in many strategic studies for China's future energy system [Hu, 2014], [ERI, 2012], [CAE, 2011], [NDRC, 2009], regional energy flow analysis for China was however only recently suggested as a research priority by China's National Energy Administration [NEA, 2013]. Furthermore few studies combine an energy system analysis for China with a detailed discussion of the underlying statistical and data quality issues.

Application areas for this China-specific regional energy flow analysis are thus targeting a broad and interdisciplinary audience. The results of this study could contribute to the following energy research areas:

(i) the analysis of regional disparities in China's current energy system [Hu, 2012], [Ma et al., 2012], [Zhang and Wang, 2012], [Li et al.,2007];

(ii) the development of national, regional and provincial policy instruments in the water-air-energy nexus, such as air quality policies and energy efficiency targets [Howarth et al., 2014], [Dong and Liang, 2014], [Da et al, 2013], [Fei et al, 2011], [Meng et al, 2011], [Auffhammer and Carson, 2008];

(iii) the modelling of future economic, energy, and emission scenarios for different sub-regions in China [Dai et al., forthcoming], [Mischke and Karlsson, 2014], [ERI, 2012], [CAE, 2011], [Liu et al., 2011] [NDRC, 2009]; and

(iv) the communication of China-specific scientific results to a broad audience, including the visualisation of data issues in China's national and provincial energy statistics [Mischke, 2013], [Guan et al, 2012], [Sinton, 2001], [Sinton and Fridley, 2000].

This paper is structured as follows: Section 2 describes the theoretical framework of this research, the analysis of energy flows. This is applied in Section 3 to conduct a regional energy flow analysis for China. Section 4 presents the results of our calculations, describing energy flow charts for East-, Central- and West-China's energy supply, transformation, and end use in 2010. The discussion of major regional energy system disparities in China takes place in Section 5, followed by a discussion of data quality issues in Section 6. The author's conclusions for policy- and decision-makers are provided in section 7. Appendix C-1 provides the data tables behind the regional analysis while Appendix C-2 provides the national energy flow analysis for easy comparison.

C.2. Theoretical framework: energy flow analysis

Energy flow analysis has a long history, dating back more than 100 years. The first Sankey diagram was developed by the Irish engineer R. Sankey in 1898 [Schmidt, 2008]. Energy flow diagrams, often also called Sankey diagrams, are nowadays a standard methodology to visualise and analyse complex systems in different application areas in science and in engineering. The system boundaries for energy flow analysis can be defined in a very flexible way, from a very small system size (such as a product, a technical system, a value chain) to a very large or even global system (such as for a country or the whole world). In the area of energy system analysis and modelling, energy flow diagrams are often used as a reference tool when comparing a country's current energy system with potential future energy scenarios [Ma et al., 2009] [Li et al., 2007]. Sankey diagrams are also a helpful and intuitive tool when communicating technical complex aspects across different disciplines and to the general public [Schmidt, 2008].

The use of energy flow charts and Sankey diagrams in China is increasing since 2005. Most of the energy flow charts for China are mapping the national energy system and are usually based on official government statistics released by NBS [Ma et al., 2009] [Li et al., 2007] [Li et al., 2011] [Cao et al, 2012]. China's Energy Research Institute started mapping the energy flow of China in 2010, however without providing for a reference for the underlying methodology [ERI, 2012]. One fuel specific energy flow diagram is also available for China, which is tracing the national use of crude oil and petroleum products in 2009 [Ma et al, 2012]. An energy flow chart for China standardised international units is annually published by the International Energy Agency, the most recent one is available for 2011 [IEA, 2014]. IEA´s internationally comparable Sankey diagram of China was recently used as a starting point for energy security analysis [Leung et al, 2014]. Different national energy flow charts are thus available for China, depending on the underlying data source and statistical definitions. A few examples of provincial energy flow analysis for China exist currently, namely for Jiangsu Province in 2008 [Zhang, Wang, 2012] and Shandong Province in 2009 [Zhang, 2011].

For the case of China and the caveats of official energy statistics, energy flow charts proved in particular useful to identify, classify, and sort comparable energy statistical data [Ma et al, 2012], [Zhang and Wang, 2011]. Some researchers started to adjust the official national energy statistics with additional data sources and methodologies to allow for a more detailed mapping of China's national energy flow and associated energy demand drivers [Ma et al, 2012]. Limited research is available that allows to precisely compare China's national energy statistics in the unit of tons of coal equivalent with energy statistics from other countries in standardised international units [Mischke, 2013], [Ma et al, 2012], [Zhang and Wang, 2011].

C.3. Practical application: analysing regional energy system disparities in China

C.3.1. Defining system boundaries of East-, Central-, and West-China

China's official statistics disaggregated the country since the 1980s frequently into three different regions or "belts", namely "the East," "the Centre" and "the West". Over the past three decades, China's regional modernisation and economic development policies have been focussed on the East, which subsequently leads to the current regional disparities in economic, energy and emission indicators within China. This paper uses the most recent official regional definitions of East-, Central- and West-China for the 12th Five-Year-Plan [NBS, 2011] to assign the available provincial units of China to one of these three regions. East-China consists of Liaoning, Beijing, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, and Hainan. Central-China consists of Heilongjiang, Jilin, Shanxi, Henan, Anhui, Hubei, Hunan and Jiangxi. West-China consists of Inner Mongolia, Shaanxi, Gansu, Ningxia, Xinjiang, Qinghai, Sichuan, Guizhou and Yunnan (Figure C-1). A similar regional definition of China is used amongst others by [Dai et al, forthcoming], [Li et al, 2013], [Huang and He, 2011], [Feng et al., 2011], [Huang and Todd, 2010], [Keidel, 2009], [Auffhammer and Carson, 2008].

Some China-specific energy system and power sector studies with a different regional boundaries of China exist, reaching from two sub-regions (East, West) to eight sub-regions (Northeast, Beijing-Tianjin, Northern Coastal, Eastern Coastal, Southern Coastal, Central, Northwest, Southwest) in line with the specific research focus and the availability of provincial data [Mischke and Karlsson, 2014] [Howarth et al., 2014].

We dealt with China-specific statistical phenomena as follows: Energy statistics for Tibet, Hong Kong and Macau are not included in this energy flow analysis. This is either due to either a lack of data in NBS energy statistics or methodological differences between energy statistics for mainland China and special administrative regions of China [Mischke, 2013], [Guan et al, 2012], [Huang and Todd, 2010], [Sinton, 2001], [Sinton and Fridley, 2000]. Furthermore, there is currently no information about biomass available from NBS's energy balances, both at national and provincial level [Mischke, 2013], [NBS, 2010].

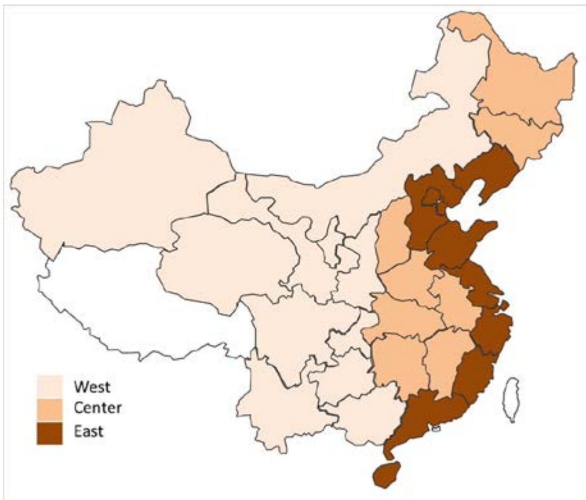

Figure C-1: Energy system boundaries of East-, Central- and West-China

C.3.2. Calculating regional energy flows in China

China's official energy balance sheets are published by the National Bureau of Statistics (NBS) in annual energy statistical yearbook. The NBS publishes these energy balances in both physical units and in energy units, namely tons of coal equivalents [NBS, 2010]. Provincial Energy Balance Sheets are only provided in physical units [NBS, 2010]. We base our analysis on the most recent available complete dataset for 2010.

In this paper, we calculate the regional energy flows for East-, Central- and West-China in 2010, as follows:

1. We collect all provincial energy balance sheets, disaggregated in the format of 30 specific fuels and energy products. We aggregate the provinces into three regions as per Figure C-1, with 30 disaggregated fuels and energy products.
2. We calculate national conversion factors fuel by fuel from the national disaggregated NBS energy balance in both physical units and in energy units (in total 30 conversion factors).
3. Without having official provincial conversion factors from physical unit to energy unit available for China, we assumed that the national conversion factors could be applied in three regions. The sums of physical data in three aggregated regions of China are then transferred from physical quantity units to energy units by applying the different conversion factors.
4. The regional energy balances in energy units are then aggregated form 30 disaggregated fuels and energy products to six major groups, as per NBS definition (see table 1 below).
5. On this basis Sankey diagrams are constructed, that follow the requirement of maintaining a regional energy balance in the unit of tons of standard coal equivalent. We trace therefore all major fuel flows (larger than 250 million tsce in 2010). The exact quantities of energy flows for East-, Central- and West-China in 2010 are provided in the Appendix in the format of NBS energy balance.

China energy balance item	Definition
Fuels and energy carriers	
Coal	aggregates raw coal, cleaned coal, other washed coal, briquettes, gangue
Oil/Petroleum Products	aggregates crude oil and the following petroleum products: kerosene, diesel, fuel oil, bitumen asphalt, petroleum coke, liquefied petroleum gas (LPG) and other petroleum products
Natural Gas/LNG	aggregates natural gas and liquefied natural gas
Other energy (OE)	surplus heat
Electricity	electricity generated from various aggregated primary energy sources: nuclear and the following renewables: hydro, wind, solar; includes further electricity output from energy transformation processes, including coal fired power plants
Energy Supply	
Domestic Production	domestic production within the regional boundaries including recovery of energy and stock change
Net international import / export	Aggregates the following categories from the provincial energy balance: International imports, Refuelling of domestic airplanes & ships in international waters, international fuel export
Net domestic import / export	Aggregates the following categories from the provincial energy balance: Moving In from Other Provinces/Regions, Domestic Airplanes & Ships Refuelling in China, and Sending Out to Other Provinces/Regions
Energy Transformation	
Electricity Generation	Power generation from fossil fuels and primary electricity in transformation processes
Refineries	petroleum refineries including petroleum product output and crude oil input
Coking	aggregates coking, heating supply, coal washing, gas works and natural gas liquefaction
Other transformation	aggregates other transformation processes, such as, direct fuel use in end-use sectors and briquette production
Loss	refers to energy losses from power stations, coal transformation processes and petroleum refining
Energy End Use	
Industrial	aggregates energy use in industry and construction sectors, includes also agriculture and non-energy use
Residential	aggregates energy use in residential sector
Transportation	aggregates energy use in Transport, Storage and Post
Commercial	aggregates energy use commercial and service sectors, including wholesale, retail trade and hotels, restaurants and other service sectors

Table C-1: Chinese statistical definitions for regional energy flow analysis

C.3.3. Benchmarking national and regional energy flows

Once the regional energy flows are calculated and visualised in energy flow charts, the presented methodology focuses on comparing the different regional energy flows with the national energy flow [NBS, 2011]. We include in our analysis the estimation of regional ratios for the share of domestic production in total primary energy supply and for the efficiency of major energy transformation processes, such as power generation.

As China's national energy balance does usually not fully balance with the sum of the provincial energy balances, we expect some data quality issues [Mischke, 2013], [Guan et al., 2012], [Sinton, 2001]. We therefore quantify potential data differences between the aggregated three regions and the national total. This benchmarking exercise will highlight and quantify major uncertainties embodied in the different NBS data sets and our methodological assumptions.

C.4. Results: regional energy flow analysis for China

This chapter presents the main characteristics of the three different regional energy flow charts for China. We follow the principle of an energy balance and highlight major aspects for energy supply, energy transformation and final energy use. For easy reference, we provide the underlying regional energy balance tables in Annex C-A1 and the national energy flow chart in Annex C-A2.

C.4.1. East-China energy flow analysis

The aggregated total primary energy supply in East-China (1798 million tsce) is dominated by coal (1129 million tsce), followed by oil/petroleum (413 million tsce). Domestic production (455 million tsce) is not sufficient to meet the region's final energy demand, as shown in Figure C-2. All fuels and energy carriers mapped in Figure 3 below show large net imports from foreign countries and other regions of China, in particular with regards to net domestic imports of coal (792 million tsce) and to a lesser extend for net domestic imports of oil/petroleum (70 million tsce). Energy transformation in East-China is also dominated by coal; most of it is required as input for electricity generation (510 million tsce) and coking (166 million tsce). Oil refining in East-China is relying mainly on international imports (213 million tsce), as the domestic production is limited (129 million tsce). The total final energy consumption in East-China (1375 million tsce) is dominated by industrial energy uses (985 million tsce) and to a lesser extent by the transport sector consumption (145 million tsce). Industrial consumption is mainly fuelled by secondary products (307 million tsce) and coal (290 million tsce), followed by electricity (192 million tsce). The consumption of refined oil products in industry (170 million tsce) is slightly higher than in the transportation sector (137 million tsce). The share of natural gas/LNG in final energy consumption is negligible (4 million tsce).

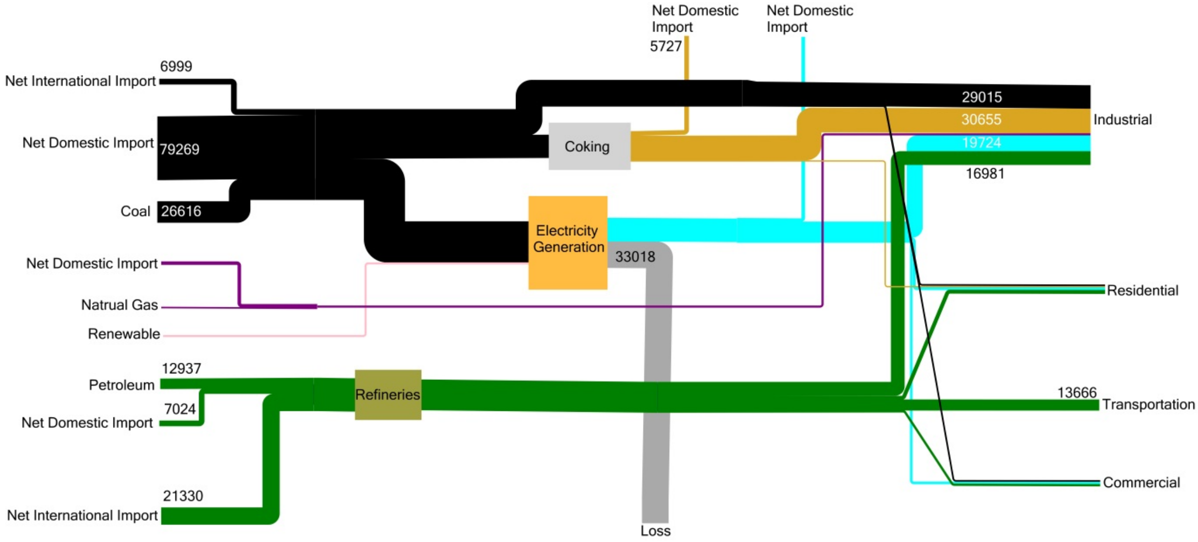

Figure C-2: Sankey Diagram of East-China in 2010 (10^4 tsce)

C.4.2. Central-China energy flow analysis

The total primary energy supply in Central-China (1006 million tsce) is dominated by coal (862 million tsce), followed by oil/petroleum (133 million tsce). Domestic production in Central-China (1908 million tsce) exceeds the regions total final energy consumption (742 million tsce), as highlighted in Figure C-3. Domestic production relies thereby on coal (973 million tsce). Figure 4 below shows accordingly major domestic net exports for coal (123 million tsce) and secondary products (65 million tsce). Energy transformation in Central-China is mainly dominated by coal; most of it is required as input for thermal power stations (313 million tsce) and coking (190 million tsce). Direct coal use in final energy is very high, for example in industrial uses (263 million tsce). Compared to coal transformation processes, oil refining in Central-China is rather small. The final consumption in Central-China is dominated by industrial uses (553 million tsce), followed by residential consumption (80 million tsce). Besides direct coal use, there is a large consumption of secondary products (135 million tsce) and a smaller consumption of electricity (88 million tsce). Natural gas consumption is negligible (2 million tsce).

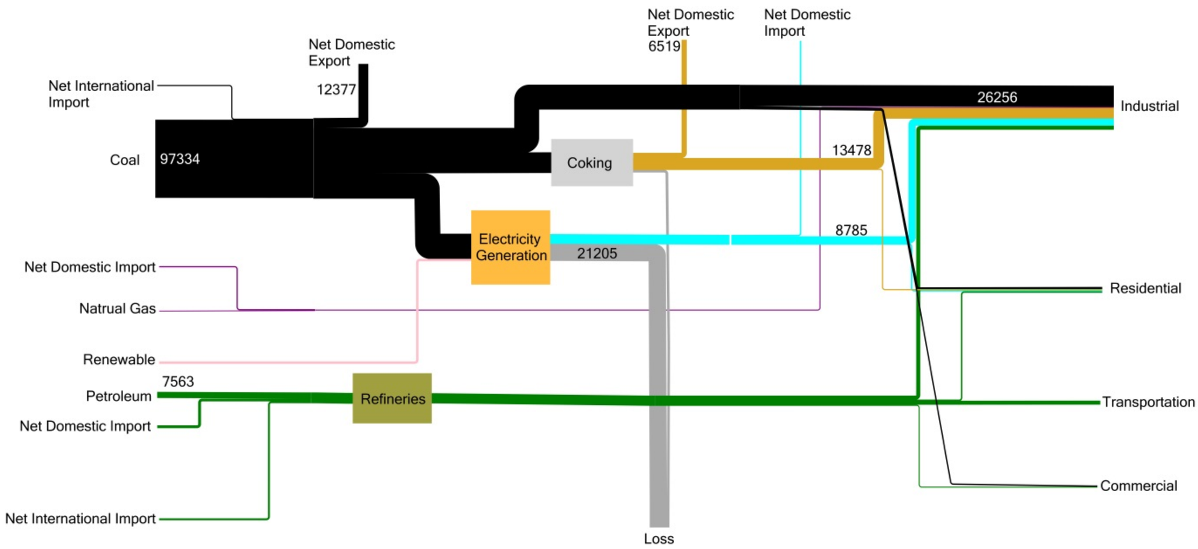

Figure C-3: Sankey Diagram of Central-China in 2010 (10^4 tsce)

C.4.3. West-China's energy flow analysis

The aggregated total primary energy supply in West-China (963 million tsce) is dominated by coal (749 million tsce) and to a lesser extent by oil/petroleum (121 million tsce). The total domestic energy production in West-China (1560 million tsce), mainly driven by coal (1244 million tsce) and natural gas (138 million tsce), exceeds the regions total final energy demand (685 million tsce). This allows for domestic net exports of coal (508 million tsce) and natural gas (74 million tsce), as shown in Figure C-4. As described before for East- and Central-China, energy transformation in West-China is fuelled by coal. Coal is required as input for thermal power stations (306 million tsce) and coking (124 million tsce). Refining is again of minor importance. The total final consumption in West-China is dominated by the industrial sector (477 million tsce). Industrial consumption relies on direct coal use (191 million tsce), followed by the use of secondary products (111 million tsce) and electricity (92 million tsce).

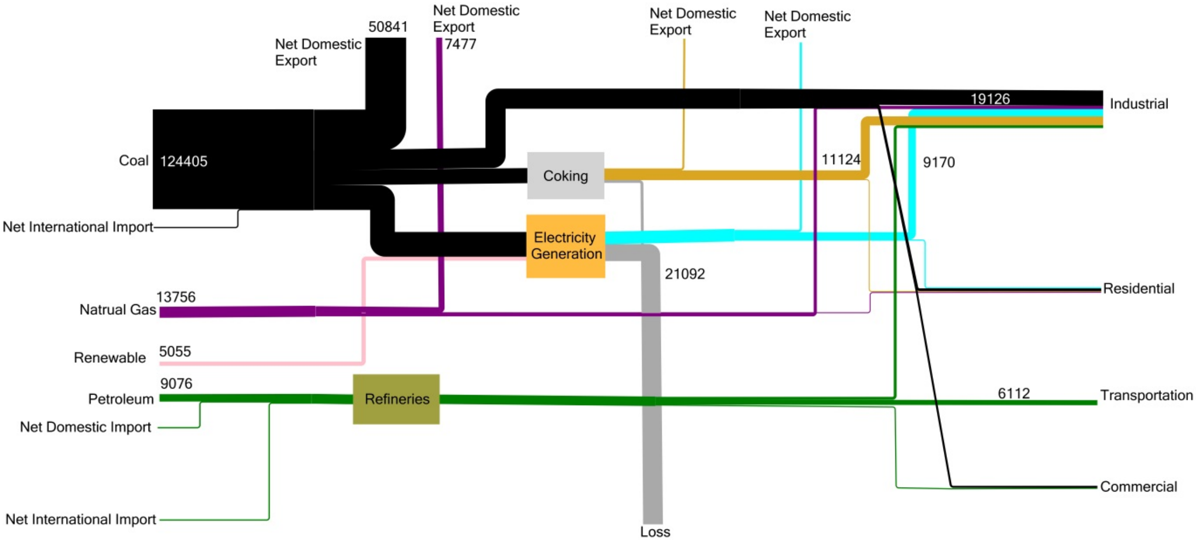

Figure C-4: Sankey Diagram of West-China in 2010 (10^4 tsce)

C.5. Discussion: regional energy system disparities in China

This chapter builds on the newly developed regional energy flow charts for China. We highlight here major disparities between the three regional energy systems and the national energy system, provided in Appendix C-2. This analysis is carried out for all major energy flows (defined as < 250 million tsce). Data quality issues are addressed in the following chapter 6.

C.5.1. Regional disparity in China's energy supply

Coal is the major fuel in China's national primary energy supply. West-China accounts for about 50%, Central-China accounts for about 39% and East-China accounts for about 11% of the national domestic coal production, see Figure C-5. Total primary energy supply of oil/petroleum products is dominated by East-China, which accounts for about 65% in the corresponding national total. East-China is also a major net-exporter of oil and petroleum products to other regions of China. Natural gas/LNG production and primary electricity from renewable and low-carbon energy sources (hydro, wind, solar, nuclear) are of minor importance, at both the national and sub-national level.

We find that ratio between total domestic production and total primary energy supply varies a lot between the three regions of China. The share of domestic energy production in primary energy supply is lowest in East-China, only about 25%. This results in major net imports for East-China. In Central-China the domestic production is almost balanced with the primary energy supply, the respective ratio is about 109%. West-China shows the highest ratio between the domestic production and the primary energy supply; namely about 163%. This allows thus for large scale net domestic exports from West-China to other regions.

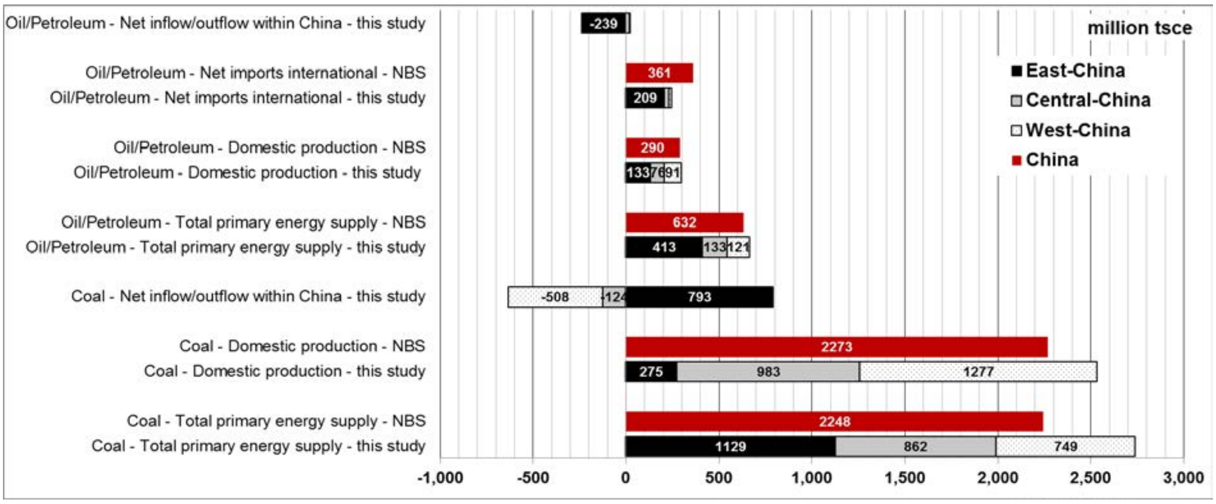

Figure C-5: Benchmarking major regional disparities in China's energy supply (million tsce, 2010)

C.5.2. Regional disparity in China's energy transformation

Power production from coal is the largest energy transformation process in 2010, both at a national level and in all regions of China, as shown in Figure C-6 below. West-China accounts for about 31%, Central-China for about 36%, and East-China for about 51% in the national coal input for all energy transformation processes. Coking takes mainly place in Central-China (about 40%) and in East-China (about 35%). These two regions produced most of the national coke output in 2010. Coal fired power generation can be mainly mapped to East-China (about 50% of the national total). Accordingly most of the coal inputs to thermal power plants are also mapped to East-China. Refining took mainly place in East-China in 2010, where about 90% of inputs for refineries can be traced.

We find regional disparities in the efficiency of major transformation processes, with East-China being the most energy efficient region. Based on the energy flow analysis carried out in this paper, some input-output based energy transformation efficiencies can be estimated. The efficiency of coking, estimated by the ratio of secondary product output and coal inputs, is different across the three regions of China. This ratio is highest in East-China (about 94%), followed by Central-China (about 92%) and lowest in West-China (about 90%). The efficiency of coal based power plants is different across the three regions of China. It is highest in East-China (about 41%), followed by Central-China (about 35%) and lowest in West-China (about 32%).

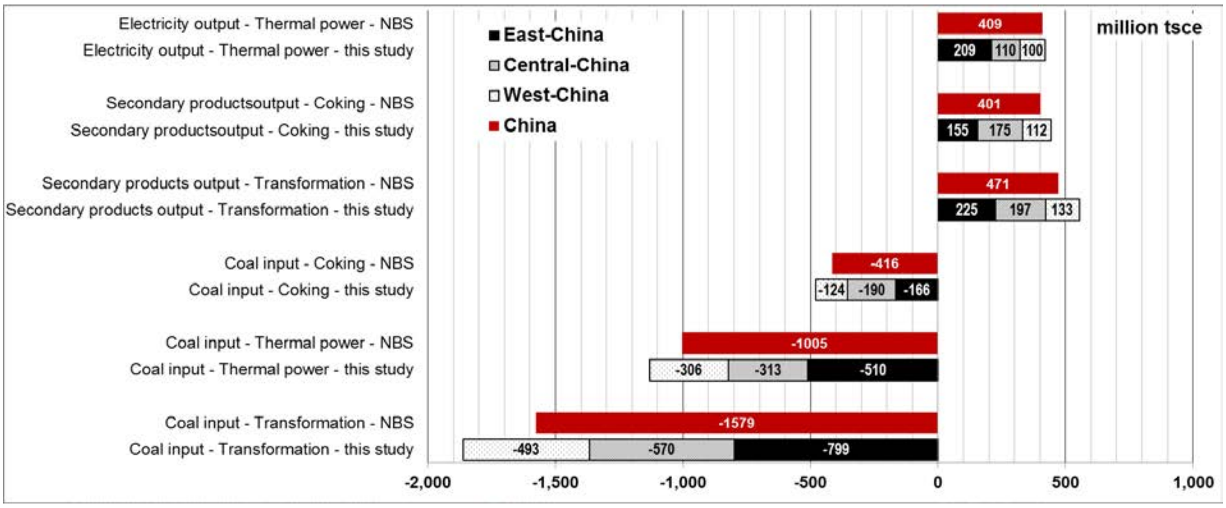

Figure C-6: Benchmarking major regional disparities in China's energy transformation (million tsce, 2010)

C.5.3. Regional disparity in China's final energy use

East-China is the region that dominated final energy consumption in 2010, as shown in in Figure C-7 below. About 49% of the total national energy use in industry can be mapped to East-China. Coal, electricity and oil/petroleum consumption in industry are highest in East-China, accounting for about 58% of the national coal use, 53% of national electricity use and about 70% of national oil/petroleum product use in industry. About 55% of China's petroleum products consumption in the residential sector and about 65% of China's petroleum products consumption in the transport sector can be mapped to East-China.

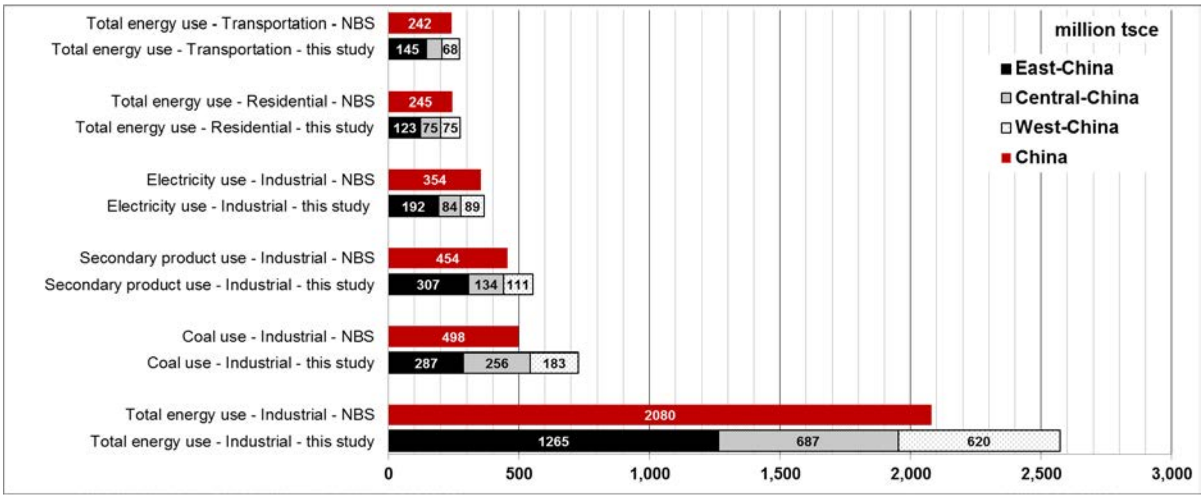

Figure C-7: Benchmarking major regional disparities in China's energy end use (million tsce, 2010)

C.6. Limitations: data quality

The discussion of data quality issues for China is important to understand the range of uncertainty in the underlying two sets of official NBS energy statistics and our applied methodology. We calculate data differences for major energy flows between national and aggregated regional energy indicators for China in both tsce and in %. A positive data difference means that the three regions combined are larger than the corresponding national energy indicator. On the other hand, a negative data difference means that the three regions aggregated are smaller than the corresponding national total. The data differences between aggregated regional and national energy balance indicators are included in the figures 5-7 discussed before. By benchmarking and comparing the national and regional energy flows in tsce, it is possible to highlight major data quality issues for specific fuels and energy carriers, as presented in table C-2. These data differences below could later serve as an estimate for uncertainty for a wide range of China-specific regional energy studies.

Energy balance section	Fuel / energy carrier	Absolute data difference to NBS national indicator (million tsce)	Relative data difference to NBS national indicator (%)	Ranking across the energy balance	Reference in this study
Energy supply	**Coal - total primary energy supply**	**+ 492**	**+ 22 %**	**3.**	**Figure 5**
	Coal - domestic production	+ 262	+ 12 %	**8.**	
	Oil/petroleum - total primary energy supply	+ 35	+ 6 %	**11.**	
	Oil/petroleum – domestic production	+ 10	+ 3 %	**12.**	
	Oil/petroleum – net international import	**- 116**	**- 32 %**	**2.**	
Energy trans-formation	Coal – input to all transformation processes	+ 283	+ 18 %	**5.**	**Figure 6**
	Coal – input to electricity generation	+ 124	+ 12 %	**8.**	
	Coal – input to coking	+ 64	+ 18 %	**5.**	
	Secondary products – output from all transformation processes	+ 87	+ 18 %	**5.**	
	Secondary products – output from coking	+ 41	+ 10 %	**10.**	
	Electricity – output from electricity generation	+ 10	+ 2 %	**14.**	
Energy end-use	**Coal - industrial energy consumption**	**+ 228**	**+ 46 %**	**1.**	**Figure 7**
	Secondary products - industrial energy consumption	**+ 98**	**+ 22 %**	**3.**	
	Electricity – industrial energy consumption	+ 11	+ 3 %	**12.**	

Table C-2: Identification of major data difference between national and aggregated regional fuel-specific energy flows in 2010

We find positive data differences for thirteen of the identified fourteen major fuel-specific energy flows. That indicates that in general the aggregated regional energy indicators are higher than the corresponding national indicator. The only exception to this phenomenon is the international net import of oil/petroleum products in 2010, where the aggregated regional energy indicators are lower than the corresponding national indicator. When ranking the fuel flows according to their size of relative data-difference, we find the highest uncertainty for direct coal use in industry(+46%); international net imports of oil/petroleum products (- 32%); coal in total primary energy supply (+22%) and secondary product use in industry (+22%). Most of the fuel-specific energy flows with larger data difference relate to coal and secondary products, as shown in table 2. In comparison, data differences with regards to electricity flows are rather small. This indicates that in particular all coal-related energy indicators, in all section of China's 2010 energy balance, need to be taken with caution.

C.7. Conclusion and policy implications

This paper aims to raise policy attention and improve the understanding of China's regional disparities in energy supply, transformation and end use. The future development of China's energy infrastructure, interlinked with regional economic development planning, needs to account for various major regional disparities in the country's energy system:

- Supply side: West-China accounts for about 50% and Central-China accounts for about 39% of the national domestic coal production. The share of domestic energy production in primary energy supply is lowest in East-China, only about 25%.
- Transformation: Coal fired power generation can be mainly mapped to East-China, about 50% of the national total. Refining took mainly place in East-China, where about 90% of inputs for refineries can be traced.
- End-use: East-China is the region that dominated final energy consumption in 2010, accounting for about 70% of national oil/petroleum product use in industry, about 58% of coal use in industry and about 53% of electricity use in industry.

The regional energy flow analysis presented here justifies the need for regional specific policy approaches in China. National level policy instruments and targets need to be complemented by regional or provincial level policy instruments and targets, accounting for the current energy system disparities. Going forward China needs to take many choices that require detailed regional energy system analysis, such as how to combat wide ranging air pollution in East-China and how to increase energy supply security through appropriate regional electricity network, pipeline and transport infrastructure investments. Combining a national and a regional energy system analysis could lead to regionally different policy targets, for example with regards to energy supply security, efficiency in transformation processes, and emission reductions.

Benchmarking of national and regional energy flows proved very useful to highlight regional energy system characteristics within China. This study identified and quantified major data differences, in particular for coal, across different sections of China's energy balance in 2010. These data differences are caused by uncertainties stemming from the assumed conversion factors in our methodology and potential statistical inconsistencies in the two different sets of underlying provincial and national energy statistics from NBS. The order of magnitude of data differences suggests an underreporting of national coal data in 2010. Recent research, that is comparable to this study, identified a 1.4 Gt gap in China's CO_2 emission in 2010, resulting from internal statistical inconsistencies between NBS's national and provincial emission statistics [Guan et al, 2012].

More comparable and transparent research, supported by improved methodologies, in collaboration with China's energy researchers and statisticians is needed to evaluate the quality and reliability of China’s national energy and emission data, year by year. In this regard, methodological differences between Chinese and international energy statistics can also be discussed. China-specific definitions of statistical reporting agents and the industrial code of economic activities needs to be benchmarked more with commonly used international statistics, as suggested by [Mischke, 2013] and [Wang, 2006]. The different energy flow charts developed in this paper could serve as a communication tool to improve the understanding of Chinese energy statistics for a broad audience, including economists, engineers, infrastructure planners, policy makers, and other non-technical experts.

Acknowledgements

The work presented in this paper is mainly funded by the Sino-Danish Centre for Education and Research (www.sinodanishcenter.dk) and the Danish Idella Fonden under an ongoing Sino-Danish PhD project at the Technical University of Denmark, Energy System Analysis Division. We furthermore gratefully acknowledge the support of Tsinghua University, Institute of Energy, Environment and Economy, for software use and China-specific statistical discussions, from the following projects: (i) Shandong Collaborative Innovation Centre of Energy Economy (2014SDXT008); (ii) Science Foundation of Ministry of Education of China (12YJCZH184); and (iii) Strategic Research Centre for 4th Generation District Heating (4DH), which has received funding from The Danish Council for Strategic Research. We are also very grateful for the constructive suggestions from the researchers associated with the International Energy Agency – Energy Technology Systems Analysis Program (www.iea-etsap.org).

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Appendix C-1: regional energy balance tables

Table C-1-1: Energy balance of East China – 2010 (10^4 tsce)

East China energy balance (2010, 10^4 tsce)	Coal	Natural gas/LNG	Secondary products/Heat	Electricity	Other energy	Oil/Petroleum	Energy total
Total primary energy supply	**112883**	**6613**	**10715**	**6977**	**1236**	**41291**	**179715**
1. Domestic production	27545	1979	0	2431	306	13251	45511
2. Recovery of energy	0	0	4837	0	202	0	5039
3. Moving In from Other Provinces/Regions	90592	4550	7709	5021	711	38445	147028
4. Import - international	7238	1469	118	0	15	23735	32576
5. Moving Out from Other Provinces	-11324	-355	-1982	-475	0	-31420	-45556
6. Export - international	-240	-1024	-15	0	0	-2876	-4156
7. Aviation/Shipping refueling - domestic	0	0	0	0	0	1313	1313
8. Aviation/Shipping refueling - international	0	0	0	0	0	-842	-842
9. Stock change	-929	-5	48	0	3	-314	-1197
Transformation (input and output)	**-79864**	**-2263**	**22515**	**20939**	**-598**	**-2975**	**-42246**
1. Thermal power	-51046	-1986	-1812	20939	-497	-429	-34830
2. Heating supply	-10518	-230	8764	0	-101	-550	-2635
3. Coal processing - coal washing	-1652	0	0	0	0	0	-1652
4. Coal processing - coking	-16563	0	15502	0	0	0	-1061
5. Coal processing - gas works	-92	-47	102	0	0	-16	-53
6. Coal processing - coke input to gas works	0	0	-45	0	0	0	-45
7. Coal processing - briquettes	7	0	0	0	0	0	7
8. Natural gas liquefaction	0	0	0	0	0	0	0
9. Petroleum refineries	0	0	3	0	0	2897	2900
10. Petroleum refineries - product input	0	0	0	0	0	-4877	-4877
Loss	16	112	155	1384	28	143	1839
Total final consumption incl. loss	**33024**	**4350**	**33256**	**27930**	**639**	**38323**	**137523**
1. Agriculture	300	0	0	532	15	1624	2471
2. Industry and Construction	28715	2628	30655	19192	596	15357	97142
3. Transport, Storage, Post	171	184	60	453	0	13666	14534
4. Other	1915	645	874	3014	0	2781	9230
5. Residential sector	1907	781	1511	3355	0	4752	12307

Table C-1-2: Energy balance of Central China – 2010 (10^4 tsce)

Central China energy balance (2010, 10^4 tsce)	Coal	Natural gas/LNG	Secondary products/Heat	Electricity	Other energy	Oil/Petroleum	Energy total
Total primary energy supply	**86222**	**2352**	**-4455**	**1060**	**2083**	**13316**	**100578**
1. Domestic production	98258	1011	0	2820	199	7560	109847
2. Recovery of energy	60	0	1937	0	80	0	2077
3. Moving In from Other Provinces/Regions	38955	1415	1289	1184	1802	9220	53866
4. Import - international	1618	0	0	12	0	2221	3851
5. Moving Out from Other Provinces	-51332	-74	-7808	-2957	0	-5689	-67859
6. Export - international	-353	0	-162	0	0	0	-514
7. Aviation/Shipping refueling - domestic	0	0	0	0	0	1	1
8. Aviation/Shipping refueling - international	0	0	0	0	0	0	0
9. Stock change	-984	0	288	0	2	3	-690
Transformation (input and output)	**-56987**	**-401**	**19665**	**11000**	**-577**	**-655**	**-27955**
1. Thermal power	-31330	-320	-1014	11000	-468	-87	-22219
2. Heating supply	-4423	-80	2862	0	-110	-226	-1976
3. Coal processing - coal washing	-1714	0	0	0	0	0	-1714
4. Coal processing - coking	-19041	0	17520	0	0	0	-1521
5. Coal processing - gas works	-473	0	380	0	0	0	-93
6. Coal processing - coke input to gas works	0	0	-83	0	0	0	-83
7. Coal processing - briquettes	-5	0	0	0	0	0	-5
8. Natural gas liquefaction	0	0	0	0	0	0	0
9. Petroleum refineries	0	-1	0	0	0	-8	-9
10. Petroleum refineries - product input	0	0	0	0	0	-334	-334
Loss	24	37	84	622	0	86	853
Total final consumption incl. loss	**30879**	**1957**	**15237**	**12060**	**1509**	**12657**	**74298**
1. Agriculture	646	0	35	380	100	1006	2167
2. Industry and Construction	25610	1207	13443	8405	683	3935	53283
3. Transport, Storage, Post	509	178	21	238	1	4877	5823
4. Other	1476	146	359	830	222	1101	4134
5. Residential sector	2612	389	1294	1585	503	1654	8038

Table C-1-3: Energy balance of West China – 2010 (10^4 tsce)

West China energy balance (2010, 10^4 tsce)	Coal	Natural gas/LNG	Secondary products/Heat	Electricity	Other energy	Oil/Petroleum	Energy total
Total primary energy supply	**74942**	**6279**	**-754**	**2277**	**1438**	**12101**	**96284**
1. Domestic production	127672	13760	0	5055	470	9076	156033
2. Recovery of energy	0	0	1837	0	464	0	2301
3. Moving In from Other Provinces/Regions	14926	958	1054	834	505	10322	28598
4. Import - international	2189	0	12	21	0	1417	3640
5. Moving Out from Other Provinces	-65767	-8435	-3455	-3563	0	-8671	-89891
6. Export - international	-811	0	-20	-69	0	-4	-905
7. Aviation/Shipping refueling - domestic	0	0	0	0	0	22	22
8. Aviation/Shipping refueling - international	0	0	0	0	0	-4	-4
9. Stock change	-3267	-4	-182	0	-1	-55	-3509
Transformation (input and output)	**-49339**	**-418**	**13257**	**10042**	**-149**	**-399**	**-27005**
1. Thermal power	-30645	-324	-536	10042	-131	-33	-21628
2. Heating supply	-3326	-77	2332	0	-18	-64	-1153
3. Coal processing - coal washing	-2506	0	0	0	0	0	-2506
4. Coal processing - coking	-12366	0	11234	0	0	0	-1131
5. Coal processing - gas works	-309	0	271	0	0	0	-38
6. Coal processing - coke input to gas works	0	0	-14	0	0	0	-14
7. Coal processing - briquettes	-20	0	0	0	0	0	-20
8. Natural gas liquefaction	0	-17	0	0	0	0	-17
9. Petroleum refineries	-167	0	-29	0	0	-40	-236
10. Petroleum refineries - product input	0	0	0	0	0	-262	-262
Loss	84	82	3	693	0	120	981
Total final consumption incl. loss	**25027**	**5884**	**12365**	**12144**	**1292**	**11781**	**68492**
1. Agriculture	805	11	47	317	42	711	1933
2. Industry and Construction	18321	3993	11077	8853	939	2649	45831
3. Transport, Storage, Post	310	306	43	233	26	6112	7030
4. Other	2361	365	178	733	90	1276	5002
5. Residential sector	3145	1127	1018	1314	195	914	7714

Appendix C-2: national energy flow chart

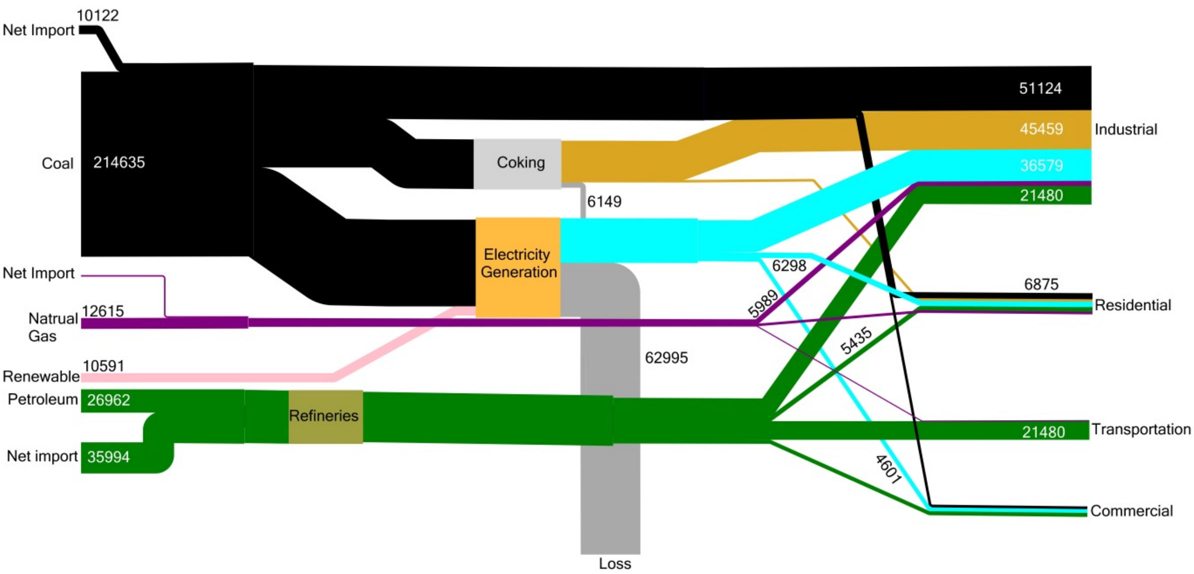

Figure C-2-1: National energy flow chart of China – 2010 (10^4 tsce)

Quantifying uncertainty in China's regional energy future towards 2050: a global model soft-linking and comparison exercise

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Invited Journal Article

APPLIED ENERGY

following a conference paper presented at the 6th International Conference of Applied Energy in June 2014 in Taipeh, Taiwan

Under review since October 2014

Abstract:

As the world’s largest carbon emitter, China is a prominent case study for scenario analysis. Uncertainty in China's future energy scenarios is however considerable. This study uses a soft-linking methodology to harmonise two complex global top-down and bottom-up models with a regional China focus. The baseline follows the GDP and demographic trends of the Shared Socio-economic Pathways (SSP2) scenario, down-scaled for China, while the carbon tax scenario follows the pathway of the Asia Modelling Exercise. We find that soft-linking allows "bridging the gap" and reducing uncertainty between these models. Without soft-linking, baseline result ranges for China in 2050 are 240-260 EJ in primary energy, 180-200 EJ in final energy, 8-10 GWh in electricity production and 15-18 Gt in carbon dioxide emissions. The highest uncertainty in modelling results can be mapped for China's future coal use in 2050, in particular in electricity production. Comparing this study with the Asia Modelling Exercise indicates that sub-regional China features, when incorporated into complex global models, do not increase uncertainty in China-specific modelling results further. These new sub-regional China features, which were explicitly developed for this study, can now be used for a more detailed analysis of China's regional developments in a global context.

Keywords: energy system analysis, scenario analysis, China, TIAM, AIM, top-down and bottom-up model soft-linking

Highlights:

- First global model comparison with harmonised socio-economic assumptions for China.
- First soft-linking study that down-scales global energy scenarios for three regions of China.
- Key results for China are benchmarked with 23 global models from the Asia Modelling Exercise
- A highly transparent, interdisciplinary and open-data approach to cope with uncertainty.

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Tables and Figures

D.1. Introduction

As the world's largest emitter of CO_2, China is a prominent and important global and national case study for scenario analysis. Numerous previous studies contributed to explore China's future energy and emission pathways (Van Vuuren, Zhou et al., 2003, Jiang and Hu, 2009, Calvin, Clarke et al., 2012, Dai, Masui et al., 2012). These studies focused on national scenarios for China in a global context without exploring regional disparities in China's economic development, industry structure, and population. Uncertainty in China's future energy and emission scenarios in a global context is considerable and needs further targeted research, as concluded by Calvin, Clarke et al. (2012) in the Asia Modelling Exercise (hereafter AME). While research on regional disparities in China is available, such as regional disparities in energy supply and consumption (Mischke and Xiong, forthcoming), these are not yet discussed in global context (Mischke and B.Karlsson, 2014). An improved regional understanding of modelling assumptions and uncertainty for China's future economy and energy system is thus needed.

Two classic modelling approaches are widely used to study the impacts of energy and climate policies on a future energy and economic system. Both approaches, either a macro-economic top-down (hereafter TD) or a technological bottom-up (hereafter BU) approach, have their own strengths and weaknesses (Böhringer, 1998, Böhringer and Rutherford, 2008). Strengths of BU models include their ability to represent a large number of discrete energy technologies in a partial equilibrium and to assess the trends and financial costs of different technological options. However, due to their structure, BU models are unable to capture the full macro-economic impacts of energy policies. TD models, including computable general equilibrium (CGE) models, are widely used to represent interactions between national economic sectors and agents. TD models are able to calculate macro-economic costs and impacts of energy policies, however with at the expense of specific sectoral or technological details.

Soft-linking existing TD and BU models emerged as a pragmatic methodology to assess a wide range of energy and climate policies in joint studies (Hourcade, Jaccard et al., 2006, Böhringer and Rutherford, 2008). Various country-specific energy model soft-linking studies were recently carried out. Chen (2005) used the MARKAL-MACRO model to generate energy and emission scenarios for China until 2050 and concluded that a carbon emission ceiling is unacceptable for China due to its high economic costs. Strachan and Kannan (2008) illustrated low-carbon scenarios for the UK towards 2050 and found that the carbon abatement cost is lower in the soft-linked MARKAL-MACRO model than in the standalone BU MARKAL model. Fortes, Simões et al. (2013) soft-linked a CGE model with a TIMES model to analyse several low-carbon scenarios for Portugal and concluded that different models suggest different carbon reduction strategies. Riekkola, Berg et al. (2013) demonstrated a highly detailed and transparent method for soft-linking a CGE model with a TIMES model for Sweden. This study confirmed a new picture of the Swedish economy's energy use with and without soft-linking.

This study soft-links a multi-region dynamic CGE model and a bottom up global energy system model, which both include three economically different regions of China in their global framework. To the best of our knowledge, no global soft-linking exercise with focus on an improved regional analysis of China was carried out yet. Possible explanations for this research gap are the methodological challenges in combining China's energy and economic data with commonly used international data (Mischke, 2013). The results from this soft-linking approach will feed into the ongoing dialogue on socio-economic development priorities and future energy and emission targets, both within China and the United Nations.

The remaining sections of this paper are structured as follows: Section D-2 describes the models and underlying databases used in this study. Section D-3 summarizes the calculations for this China-specific soft-linking and model comparison exercise. Section D-4 presents the results at a global, China-national and China-regional scale. The results are discussed in section D-6. Conclusions and an outlook for further research are given in section D-7. More detailed model descriptions are provided in the appendices. All calculation results are provided as supplementary material.

D.2. Materials and methods

D.2.1. Soft-linking two global models with a regional China focus

We have selected two global models that are able to represent similar regional features of China's energy and economy to provide new insights for China's future energy system. A joint research effort between Japan's National Institute of Environmental Studies, the Technical University of Denmark and China's Energy Research Institute allowed to soft-link the AIM/CGE-China (hereafter CGE) model and the TIMES Integrated Assessment Model (hereafter TIAM). This CGE model is a global top-down general equilibrium model that represents 22 economic sectors for the Chinese and global economy. TIAM is a technology-rich, bottom-up model that represents the global energy system and energy-dependant economic sectors. TIAM is being developed by multiple energy research groups under the International Energy Agency's Energy Technology Systems Analysis Programme (IEA ETSAP) and documented in (Loulou, Remme et al., 2005, Loulou and Labriet, 2008, IEA, 2013). The underlying structures and core functionalities of both models are provided in the appendices. This chapter focuses on major common model properties to highlight the benefits of soft-linking these two independently developed global models for a China-specific study.

Both models are based on an optimisation framework. Within the optimisation framework of the CGE model the individual behaviours of households, firms and government are based on market clearance, zero profit and income balance conditions to solve simultaneously for the set of prices and the allocation of goods and factors that support general equilibrium (Sue Wing, 2009). The TIAM framework is based on the optimization of total energy system costs, specified as the discounted sum of the annual costs minus revenues, under a set of technical, economic and policy constraints.

Both models are able to represent energy-intensive industries with a high level of detail. The energy-intensive industries in a model region are distinguished as separated sectors in both models. This applies to iron and steel industry, non-metal mineral industry, chemical industry, and pulp and paper industry. For the case of China, these industries accounted for about 13% of China's GDP in 2007 (NBS, 2011) and consumed about 40% of China's final energy in 2008 (NBS, 2008). The level of detail for other sectors, such as transport, residential, public and commercial services differs between both models.

Both models use a consistent division of global and China-specific regions. The China-specific regional feature in both models is in particular developed for this soft-linking study. We define East-, Central- and West-China based on the country's Seventh Five-Year Plan (NPC, 1985), which proposed three major economic zones to promote economic specialization and division of labour within China. The geographic regions in both models are summarized in the Table D-1 below. These are classified by commonly used geographic and statistical area codes in line with the United Nations (UN, 2014) and the National Bureau of Statistics of China (NBS, 2011).

Table D-5: Global model regions in the CGE model and TIAM

Nr.	CGE and TIAM model regions	Geographic regions in line with the UN statistical system	Provincial units in line with the Chinese statistical system
1	Africa	several countries in the Eastern Africa, the Middle Africa, the Northern Africa, the Western Africa, and the Southern Africa regions	
2	Australia-New Zealand	Oceania region	
3	Canada	Canada as part of the Northern America region	
4	Central and South America	several countries in the Central America, the South America, and the Caribbean region	
5	**East China**	**China as a part of the Eastern Asia region**	**Liaoning, Beijing, Tianjing, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Hainan, Guangxi**
6	**Central China**		**Heilongjiang, Jilin, Inner Mongolia, Shanxi, Henan, Anhui, Hubei, Hunan, Jiangxi**
7	**West China**		**Shaanxi, Gansu, Ningxia, Xinjiang, Qinghai, Sichuan, Guizhou, Yunnan**
8	Eastern Europe	several countries in the Eastern Europe and the Southern Europe regions	
9	Former Soviet Union	several countries in the Eastern Europe and the Western Asia regions	
10	India	India as part of the South-Central Asia region	
11	Japan	Japan as part of the Eastern Asia regions	
12	Mexico	Mexico as part of the Central America region	
13	Middle East	several countries in the South-Central Asia and the Western Asia regions	
14	Other developing Asia	several countries in the South-Central Asia, and the South-Eastern Asia regions	
15	South Korea	South Korea as part of the Eastern Asia region	
16	United States of America	USA as part of the Northern America region	
17	Western Europe	several countries in the Northern Europe, and the Western Europe regions	

D.2.2. Global and China-specific data

Most of the global data in the CGE model are based on GTAP 6 (Dimaranan and V., 2006) and IEA (IEA, 2009). China-specific provincial data sources are the 2002 inter-regional input-output tables (Li, Qi et al., 2010) and the 2002 energy balance tables (NBS, 2003). TIAM is calibrated with national energy balances from IEA (IEA, 2005-2013). Learning curves and future cost assumptions for technologies are a key model input, derived from a wide range of literature sources. A detailed methodology to construct the regional energy balances to represent China in TIAM while ensuring international comparability was developed specifically for this study (Mischke, 2013). In this methodology, bottom-up energy balances of East-, Central- and West-China are constructed based on China's provincial energy balance tables (NBS, 2003-2013) and IEA's national China energy balance.

D.3. Calculations

The soft-linking methodology applied here will serve as an analytical framework for our China-specific global model comparison and scenario analysis (see Figure D-1). This methodology builds on our previous work, which was limited in scope and tested only for the China regions in both models (Dai, Mischke, 2014). In this study we expand and document the iterative soft-linking methodology for these two global models and discuss our scenario assumptions for a subsequent model comparison with a focus on China.

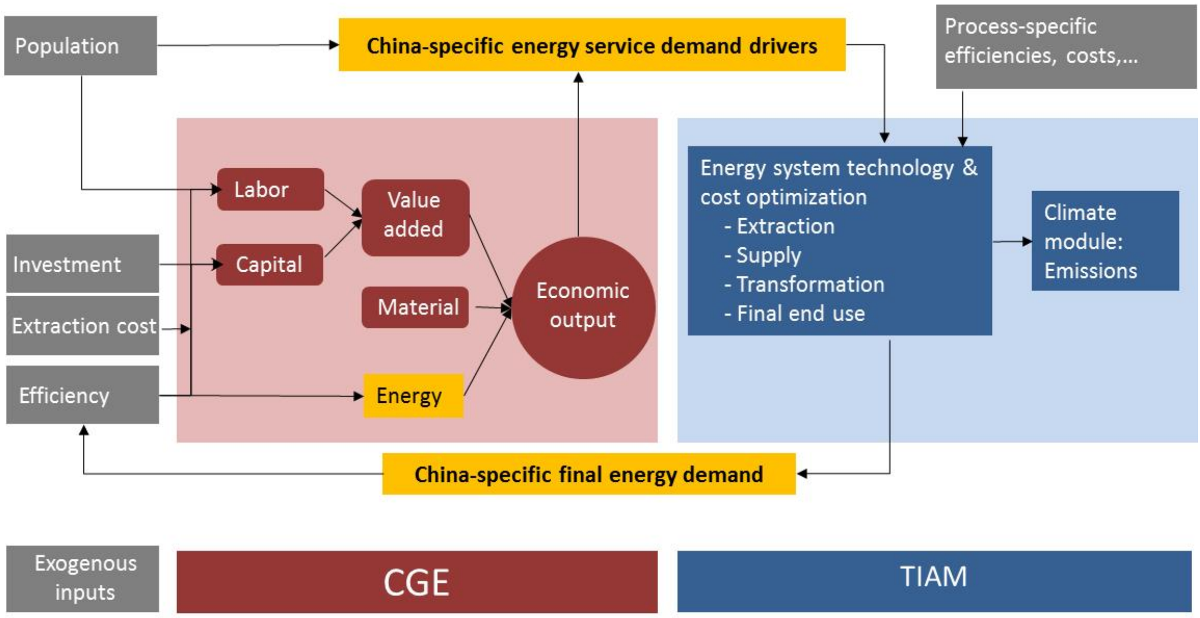

Figure D-10: Soft-linking framework between the two global models – example for the China region

D.3.1. TD to BU linking – energy service demand drivers

As shown in Figure D-1 above, the CGE model provides inputs for the bottom-up energy system TIAM model as follows: the top-down outputs for economic sectors provide bottom-up energy service demand drivers for final energy use sectors. The TD to BU soft-linking approach suggested by Riekkola, Berg et al. (2013) was applied. As it is not possible to link all economic sectors of the top-down model with energy end use sectors in the bottom-up model directly, we use different pragmatic "translation" methods to derive energy service demand drivers for the BU model from the TD model and alternative sources: (i) a direct linking based on the development within common sectors in both global models; (ii) an indirect linking based on the development of alternative sectors in both global models; and (iii) using alternative projections from other sources as no linking of sectors is possible. Table D-2 below gives an overview on the applied TD to BU linking methods in this study.

Table D-6: TD-BU linking to provide energy service demand drivers

Translation methods	BU energy service demand sector from the TIAM/China-Model	TD economic sector from the AIM/CGE-Model
Direct linking	Chemical industry energy demand Pulp and paper industry energy demand Non-metallic mineral industry energy demand Energy demand in other industry segments (aggregated) Energy demands from commercial/public heating, cooling, hot water supply, lighting, cooking, refrigeration, electric appliances, other commercial demands Energy demand from agriculture energy uses	Chemicals Paper production Non-metal production Other manufacturing Service Agriculture
Indirect linking	Iron and steel industry energy demand Non-ferrous metal industry energy demand Energy demand from residential cooling, refrigeration, cloth washing, cloth drying, dish washing, electric appliances, other residential demands	Metal smelting and processing Metal smelting and processing Household income
No linking – using alternative projections from other sources	Non specified energy industry demand Non-energy use in industry Rail transport – Energy demand by freight trains Aviation – Energy demand by domestic and international airplanes Water transport – Energy demand by domestic and international ships Road transport – Energy demand by personal cars, light vehicles, commercial trucks, medium size trucks, heavy trucks Energy demand from residential lighting Road transport – Energy demand by busses, two-wheel vehicles, three-wheel vehicles Rail transport – Energy demand by passenger trains Energy demand from residential hot water supply and cooking Energy demand from residential heating	not available, therefore based on projections for GDP and population from other sources (see chapter 3.3)

D.3.2. BU to TD linking – energy efficiencies

As shown in Figure D-1 above, after TIAM calculates the optimal technology mix and final energy demand in different sectors, the energy efficiency parameters of the CGE-Model model will be adjusted for China so that the energy consumption matches the TIAM results. After this BU to TD linking, the results of energy service demand in the CGE model will likely change. If the change is significant, the new values will be passed to TIAM again. Without soft-linking, the energy efficiency parameters refer to the values reported in the literature. When soft-linking these are associated with an exogenous autonomous energy efficiency improvement (AEEI), which is provided as the energy consumption from TIAM.

D.3.3. Defining harmonised global scenarios with a regional focus on China

Two core scenarios are modelled in this study, a baseline and a carbon tax scenario. The focus of this study is a thorough data collection, model comparison and soft-linking with a focus on China. Therefore the number of analysed scenarios is kept to a minimum. We chose to focus on comparing results calculated "stand-alone" by both models and "soft-linked" to better understand and quantify uncertainties in China's future economic, energy, and emission indicators. Soft-linking is applied in this study as a methodology to efficiently harmonise and compare scenarios between two complex global models. This methodology resulted in an iterative process, which required multiple scenario runs for testing and bug-fixing in both models, until baselines were satisfactorily harmonised for soft-linking.

Baseline scenario

The baseline scenario follows the GDP and demographic trends of the newly developed Shared Socio-economic Pathways (SSP2) scenario. SSP2 is characterized by moderate economic growth, fairly rapid growing population and lessened inequalities between industrialised, emerging and developing world regions (O'Neill, Kriegler et al., 2013). Following this storyline, the future GDP growth rates of emerging and developing countries will be higher than those for industrialised countries.

As SSP2 does not provide regional economic and demographic trends for China, this study down-scales the national GDP and population scenarios of China provided by SSP2 to a regional level of China. In line with the principle of SSP2, we assume the growth rates of central and western regions of China will be higher than in eastern, coastal China in the future. This assumes that the regional development gap within China will be narrowed. The total numbers of GDP and population of all regions of China are calculated by the following two equations: Equations (D-1) and (D-2). The resulting down-scaled indicators for different regions in China add up to the corresponding national total of the SSP2 scenario. Values in Table D-3 below imply that the per capita GDP of West and Central China will increase faster than the one in East China and the Rest of World.

$$\text{Indicator}(r, i, t) = \text{SSP2}(\text{“China”}, i, t) * \text{share}(r, i, t) \qquad \text{Equation (D-1)}$$

$$\text{share}(r, i, t) = \text{share}(r, i, t0) * \text{trend}(r, i)^{(t-t0)} \qquad \text{Equation (D-2)}$$

Where

Indicator(r, i, t)	Indicators of i - GDP, population in province r and time t;
SSP2("China", i, t)	SSP2 scenario of China in t;
share(r, i, t)	share matrix that downscales national data into provincial data, the reference year, t0, is 2002 for population and 2010 for GDP;
trend(r,i)	Changing trend of share of indicator i (Table 3).

Table D-7: Downscaling the SSP2 scenario for China in the CGE model

SSP2	East-China	Central-China	West-China
trend(r, "GDP")	0.998	1.002	1.003
trend(r, "population")	1	1	1

On this basis, the resulting socio-economic assumptions used for the baseline scenario in this study are summarised in Table D-4. The per capita GDP of East and Central China is expected to surpass the Rest of World region in around 2025 and 2035, respectively.

Table D-8: Socio-economic assumptions for three regions of China in a global context

Model Region	Population (million)					Per capita GDP (USD/capita)				
Year	2005	2020	2030	2040	2050	2005	2020	2030	2040	2050
East China	552	582	583	566	533	2541	8681	15265	21024	26738
Central China	452	477	478	463	437	1273	5375	10002	14236	18206
West China	288	303	304	295	278	1027	4056	7491	10950	14716
China	1292	1363	1364	1324	1248	1760	6494	11692	16405	21074
Rest of World	5176	6236	6884	7446	7899	8460	10180	11919	13782	15978
World	6468	7599	8248	8770	9147	7122	9519	11881	14178	16673

Carbon tax scenario

An economy wide CO_2 tax is applied to all sectors and all regions, in line with the corresponding baseline scenario described above. The carbon tax starts in 2013 with 21 USD/ton-CO_2 and follows the low carbon tax price path of the AME (Calvin, Clarke et al., 2012). In 2050 the carbon tax reaches 128 USD/ton-CO_2.

D.4. Modelling results

This chapter shows the main results of our model comparison study, highlighting results for three regions of China in a global context across models. In order to allow other researchers to easily compare and benchmark their China energy scenarios with our work, we harmonised all figures with regards to:

(i) Quantitative energy, electricity and emission indicators,
(ii) Geographic boundaries,
(iii) Time scale, and
(iv) Colour codes.

In general we find that soft-linking is useful to "bridge the gap" and reducing uncertainty between different top-down and bottom-up results for primary energy, final energy, electricity and CO_2 emissions. In the context of this study, uncertainty is defined as the data range for the same quantitative energy indicator calculated by different complex global models under harmonised socio-economic scenario assumptions.

D.4.1. Primary energy production – baseline scenario comparison

The primary energy production is in the same order of magnitude in the baseline scenario of all models, in all model regions and all model years (see Figure 2). Uncertainty remains high in the following aspects:

- TIAM shows a higher primary energy use in the Rest of World region than the CGE model, while the CGE model shows a higher primary energy use in China than TIAM.
- The primary energy mix in the CGE model is less diversified than in TIAM.
- The CGE model projects a peak in primary energy production in 2040 in China, while TIAM not.

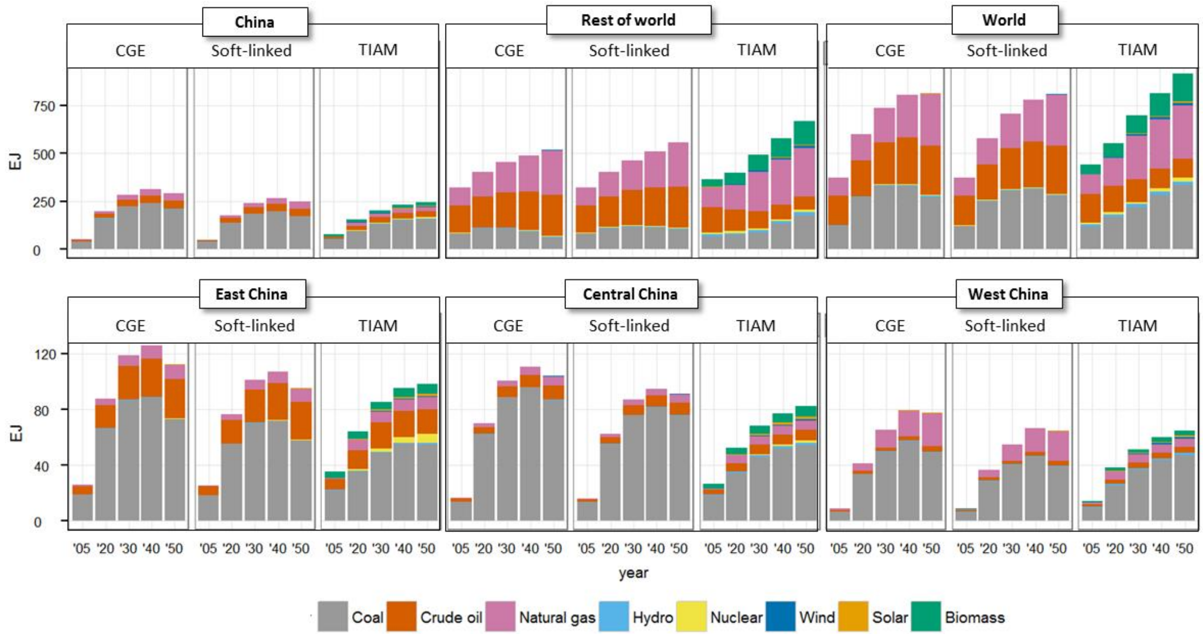

Figure D-11: Primary energy use –baseline across models (2005-2050)

D.4.2. Final energy use – baseline scenario comparison

The final energy use across models is in the same order of magnitude in the baseline scenario, in all model regions, all sectors, all fuels and all model years (see Figures D-3 and D-4). As discussed before for primary energy, uncertainty remains in the following aspects:

- The CGE model shows a slightly higher final energy use than TIAM.
- The final energy mix by fuel is more diversified in TIAM than in the CGE model.
- The sectoral composition of final energy use varies slightly, e.g. TIAM projects higher transport energy use than the CGE model.
- The CGE model projects a peak in final energy use in 2040 in East- and Central-China, while TIAM not.

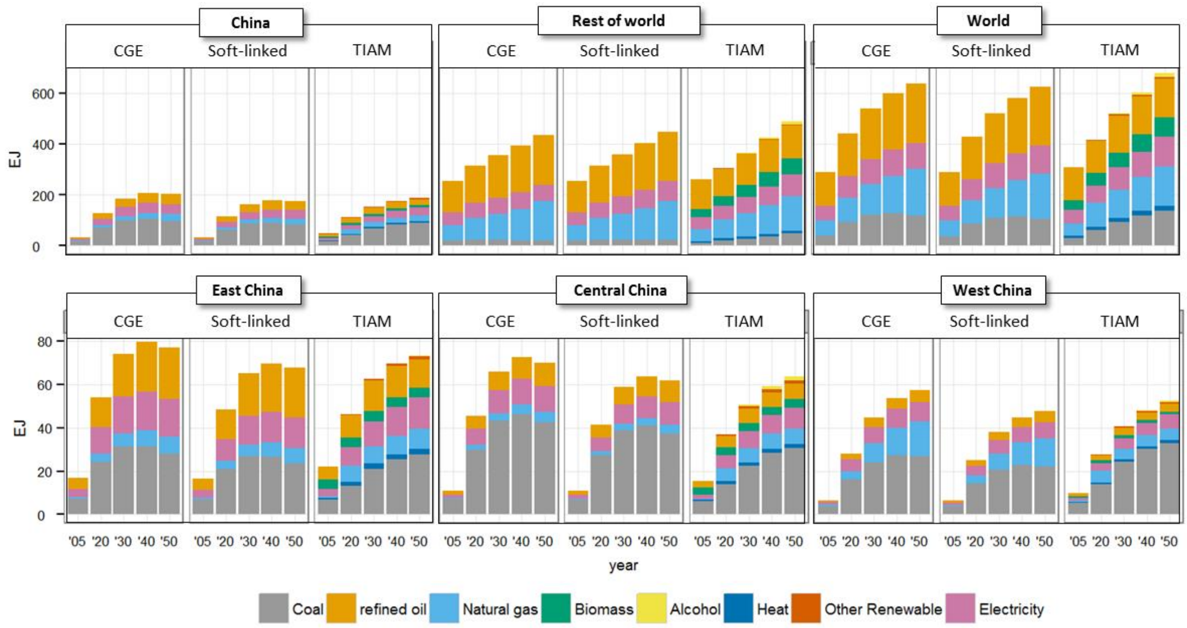

Figure D-12: Final energy use by fuel –baseline across models (2005-2050)

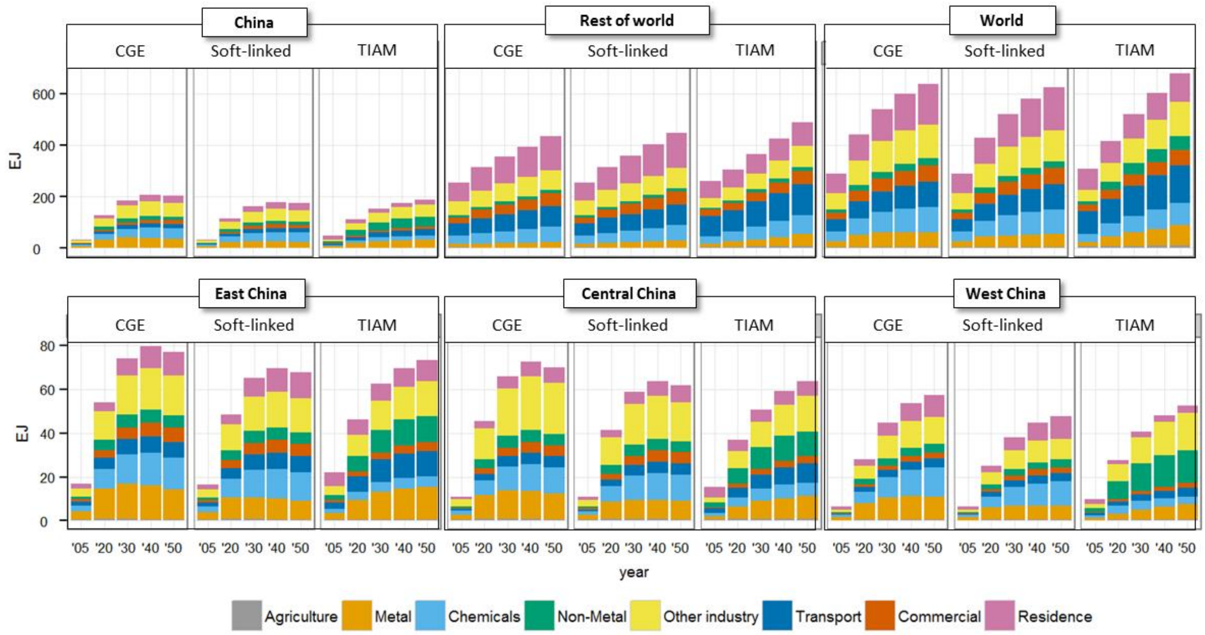

Figure D-13: Final energy use by sector-baseline across models (2005-2050)

D.4.3. Electricity use – baseline scenario comparison

Electricity use across models is in the same order of magnitude in the baseline scenario, in all model regions and all model years (see Figure D-5). Uncertainty in electricity projections is lower than in primary and final energy. Nevertheless some minor differences can be identified when comparing the different models:

- The CGE model shows higher results for China than TIAM, but lower results for the Rest of World region.

- The CGE model projects a stabilisation or peaking of electricity use towards 2050 in China, while TIAM not.

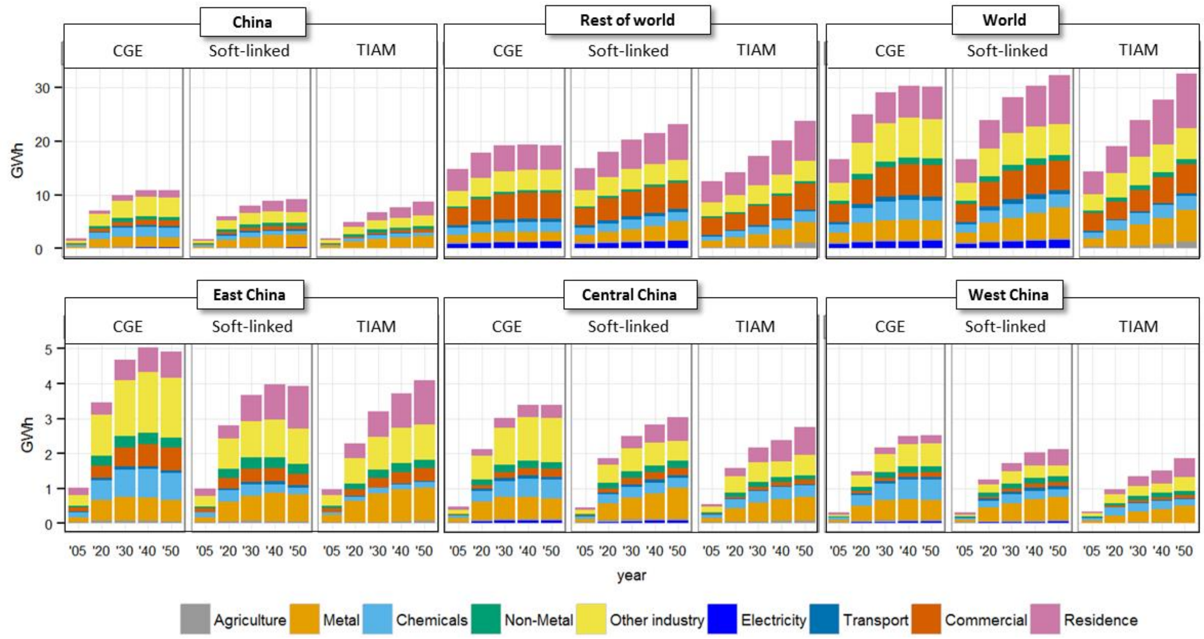

Figure D-14: Electricity use by sector-baseline across models (2005-2050)

D.4.4. Carbon dioxide emissions – baseline scenario comparison

Production-based CO_2 emissions tracked across models are in the same order of magnitude in the baseline scenario, in all model regions and all model years (see Figure D-6). The largest share of total CO_2 emissions tracked is related to power production. In order to compare CO_2 emissions across different models, we exclude in this study emission mitigation measures available in TIAM, such as carbon capture and storage. Uncertainty in CO_2 emissions, in particular at a sectoral level, increases towards 2050. Furthermore different models follow slightly different pathways for emission reduction. This includes the following main differences between models:

- The CGE model shows in general higher results for CO_2 emissions in China than TIAM.
- The CGE model shows a steeper increase in CO_2 emissions in the short term than TIAM.
- The CGE model shows an emission peak in 2040 globally, consistent with a 2040 emission peak in China. TIAM only projects an emission peak in 2040 in East-China.

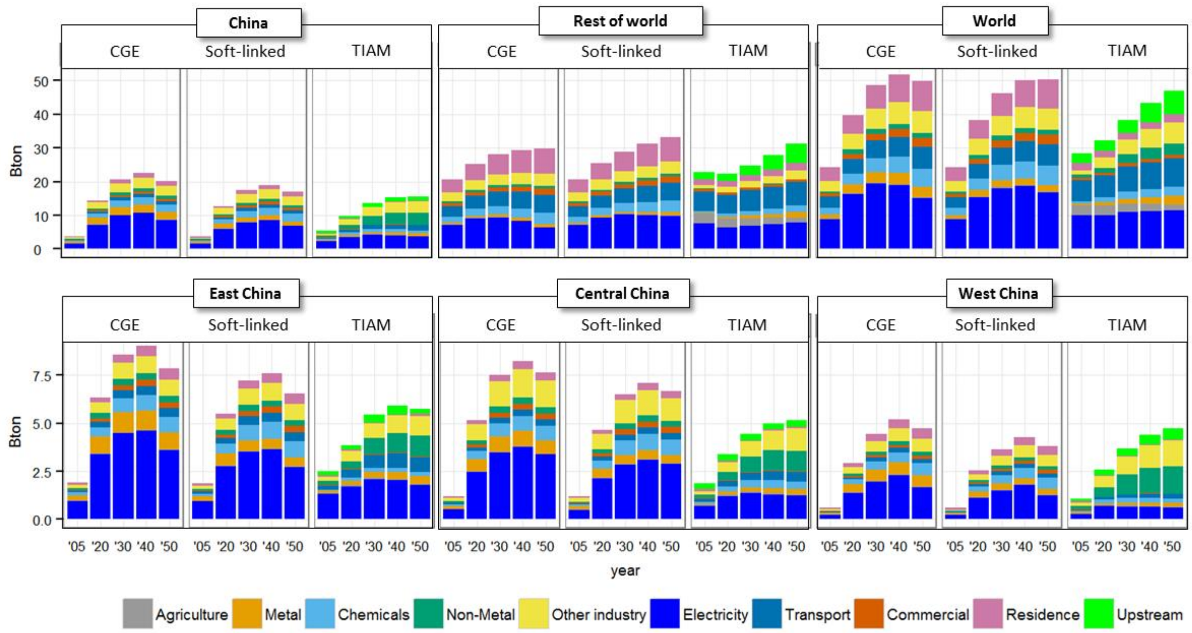

Figure D-15: CO_2 emissions by sector – baseline across models (2005-2050)

D.4.5. Carbon dioxide emissions – carbon tax scenario comparison

As in the baseline scenario, production-based CO_2 emissions across models remain in the same order of magnitude under the carbon tax scenario, especially at a global level. As already observed in the baseline scenario, sectoral CO_2 emissions reduction potentials are different across models, in particular for China. Accordingly uncertainty in this quantitative indicator is very high, as different models in this study provide different quantitative emission reduction projections under the same economy wide carbon tax. Detailed results are provided in Figure D-7 below, which is highlighting uncertainty as follows:

- China's CO_2 emissions are projected to peak about one decade earlier in the CGE model than in TIAM.
- TIAM shows a much lower emission reduction potential for all regions of China than the CGE model.

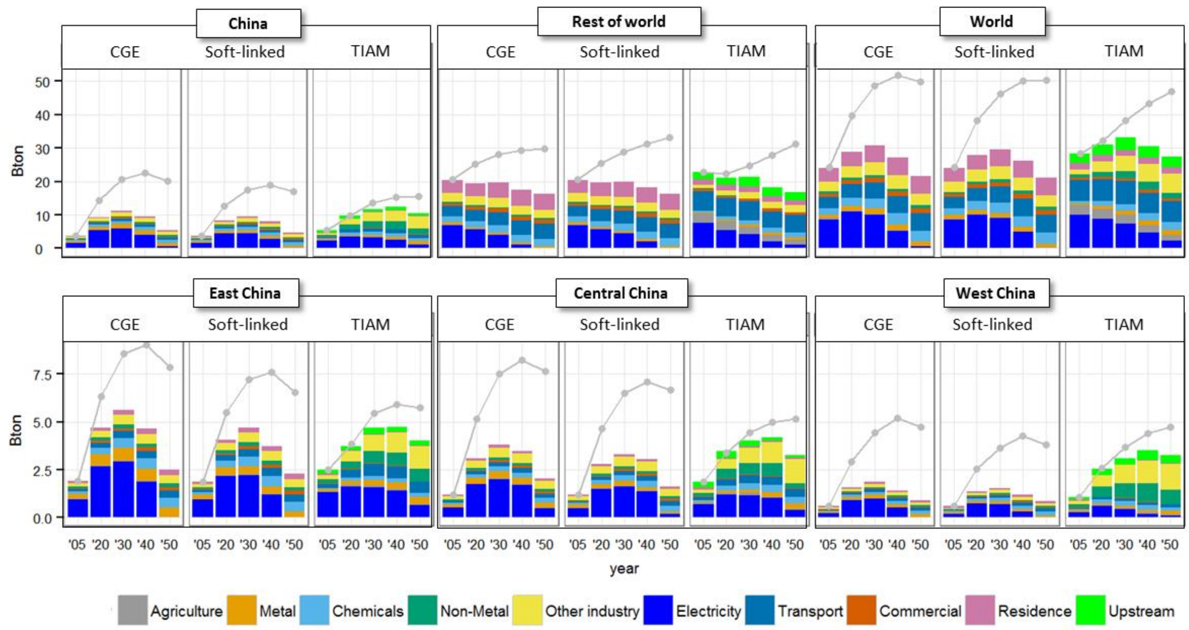

Figure D-16: Sectoral CO_2 emissions - carbon tax scenario compared to baseline (2005-2050)

D.6. Discussion

D.6.1. Comparison of results with leading global studies

The Asia Modelling Exercise coordinated by the Joint Global Change Research Institute of the Pacific Northwest National Laboratory and University of Maryland, USA, is chosen as a benchmark for our work, as it is the most recent and most transparent Asia and China specific model comparison. In total 23 global energy-economic and integrated assessment models from research institutions based in Asia, Europe, and North America participated.

The soft-linked CGE-TIAM model and both models used stand-alone appear in the range of the AME models' projections for the baseline and the carbon tax scenario. The soft-linked CGE-TIAM model appears in the medium range of the AME projections for most quantitative indicators discussed in this study, such as primary energy, final energy and carbon dioxide emissions. This can be observed for both the baseline and the carbon tax scenario (see Figures D-8 and D-9). As expected some uncertainty remains when comparing quantitative indicators in future scenarios across many different complex global models. The TIAM baseline scenario falls slightly out of the AME range for global emissions (lower than AME as shown in Figure D-8). The CGE model's baseline scenario falls also slightly out of the AME range for primary energy in China from 2005-2040 (higher than AME as shown in Figure D-8)

In general we find that, when comparing this study with the AME, that regional China features, when incorporated into global models, do not increase uncertainty in global and China-specific scenarios further. These new regional China features, which are now available in both complex global models, could therefore assist in exploring China-specific reasons of uncertainty in quantitative energy and emission indicators.

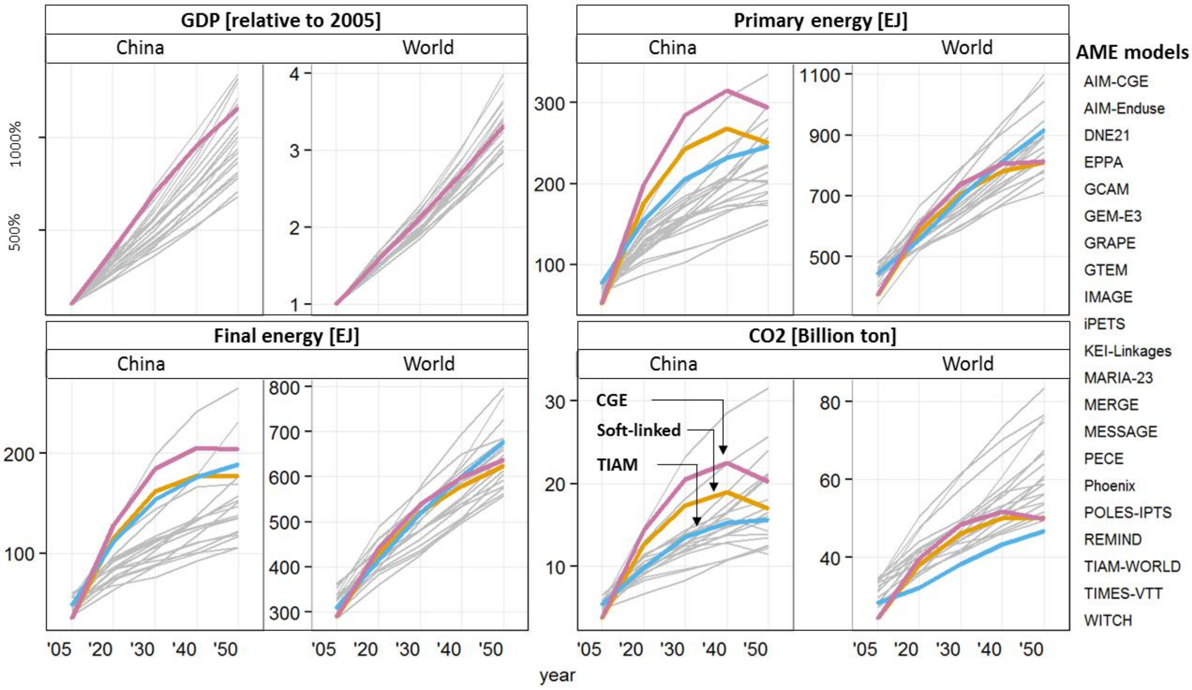

Figure D-17: Benchmarking of baseline scenarios in this study against global AME models (2005-2050)

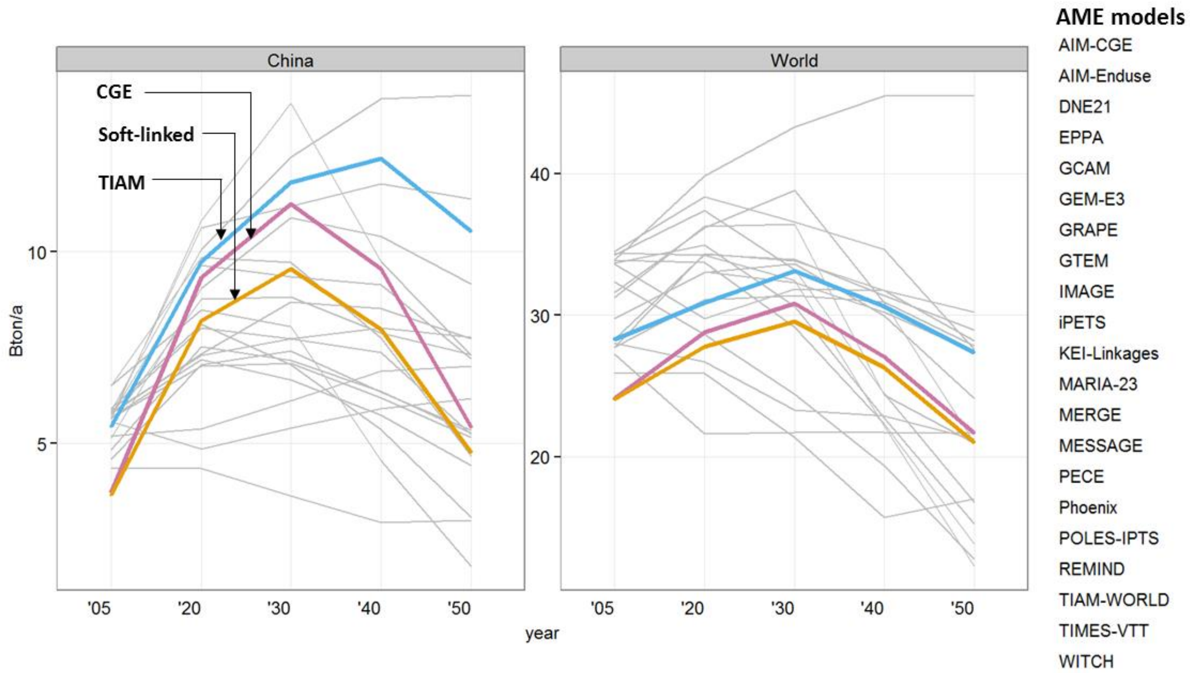

Figure D-18: Benchmarking of carbon tax scenarios in this study against global AME models (2005-2050)

D.6.2. Exploring uncertainty with a focus on China

Without soft-linking, baseline result ranges for China in 2050 are 240-260 EJ in primary energy, 180-200 EJ in final energy, 8-10 GWh in electricity production and 15-18 Gt in carbon dioxide emissions. In this study, the highest uncertainty remains for China's future coal use while the lowest uncertainty is shown in China's future electricity use.

Figure 10 below presents major quantitative calculation results for China's energy use in 2050 and benchmarks the CGE and soft-linked CGE baseline results to the TIAM baseline results. The higher the energy indicator in Figure 10 is, the higher the "disagreement" (uncertainty) between the modelled results for baseline energy use in China. Positive values indicate a higher result in TD modelling and vice versa negative values indicate a higher result in BU modelling. In this regard, soft-linking and model comparison was useful to locate uncertainty in complex global models, such as the two models in this study. Future studies applying complex global models could therefore focus on an improved soft-linking and modelling of China's future coal use, in particular coal use for power generation.

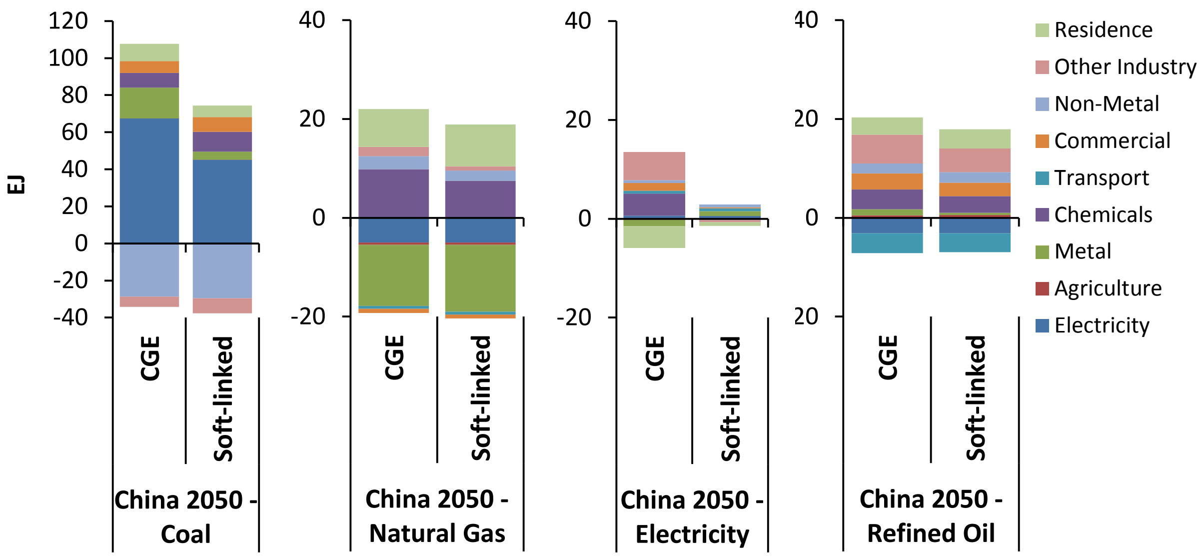

Figure D-19: Identifying uncertainty in China's energy use (baseline, 2050, CGE and soft-linked model benchmarked to TIAM)

D.6.3. Discussing reasons of uncertainty with a focus on China

As expected, differences between the two existing, complex global models remain, although the baselines and datasets between the models were harmonized as best as possible. The main reasons for this uncertainty are different underlying modelling frameworks. This is for example visible in a peaking of energy and emissions in the CGE model after 2040. As the GDP growth rate for China drops to under 2%, whereas energy efficiency remains around 2-3%, the energy consumption will peak and decrease.

Furthermore, differences in modelling results for China can be partly explained by different technology representation and different statistical inputs in both models.

(i) Different technology representation for China: The CES function in the CGE model tends to guarantee a smoother technology transformation, which implies that the future technology mix in a sector would not be so much different from that of the base year; and non-existent technology in the base year is hardly available in the future. TIAM allows for more drastic technology switches, in particular under carbon tax scenarios. In TIAM, technology change occurs in non-metal production, iron, steel and non-ferrous sector in China, where new advanced technologies use electricity and gas instead of coal as fuel input. Therefore, TIAM calculates lower coal consumption in these sectors and higher electricity and gas consumption than the CGE model.

(ii) Different statistical inputs for China: The CGE model uses China's input-output table, in which the transport sector only captures commercial transport but excludes private transport by households and transport services provided by other industries. Therefore, oil products consumed by vehicles in other industries and households are accounted in those sectors, rather than the transport sector in international statistics. TIAM is based on the internationally commonly used IEA's energy balance table, in which the transport sector accounts both commercial and non-commercial transport services. Therefore, TIAM indicates a higher use of refined oil in the transport sector, followed by chemical sector, than the CGE model. Statistical differences also explain slightly different base year values between TIAM and the CGE model.

D.7. Conclusions and outlook

The soft-linking and model comparison methodology used here enhances interdisciplinary research collaboration and promotes team-spirit across different economic and technical modelling disciplines. The range of uncertainty of modelling results can be explored with a highly standardised, transparent, and open-data approach. As this allows identifying major results differences faster, it accordingly helps harmonising baseline and scenario assumptions better. Soft-linking increases knowledge about the strengths and weaknesses of different types of models as well as their underlying databases and assumptions. This might also highlight future areas of research and development for those complex models.

Drawbacks of this soft-linking and model comparison methodology are that it is extremely time-consuming and not a straight-forward process. A balance needs to be kept between pragmatism, e.g. with regards to level of detail and data requirements in a model, time and budget constraints of a study, and the scientific quality of the underlying methodological framework. Limits of the soft-linking methodology appear when down-scaling from a global level to a regional level, when baselines and databases across models are not fully harmonised. Further research is needed in this regard.

Overall, this study aims to increase the understanding of uncertainty around future quantitative energy, electricity and CO_2 emission indicators for China, both at a regional, a national, and a global level. As previous China scenario studies showed, future energy and climate policy targets for China result in a wide range of uncertainty with regards to projected energy, electricity and emission indicators. This study concludes that it is beneficial to compare and to soft-link complex global models to bridge the "gap" between different quantitative top-down and bottom-up results for

China, provided that baseline assumptions and underlying databases are carefully harmonised. In general, a highly transparent and highly interdisciplinary modelling and soft-linking framework is suggested to further reduce uncertainty in future energy scenarios for China. We suggest that energy and emission policies for China, such as economy-wide carbon taxes, should be based on different types of models in order to identify, quantify and evaluate uncertainty of results for a more informed policy and decision making.

Acknowledgements

Financial support for this research from the following sources is gratefully acknowledged: (i) the Sino-Danish Centre for Education and Research (www.sinodanishcenter.dk); (ii) the Danish Idella Fonden; and (iii) the Environment Research and Technology Development Fund (A-1103) of the Ministry of the Environment, Government of Japan.

We would like to thank all Chinese colleagues from the Chinese Academy of Sciences, the Energy Research Institute of the National Development and Reform Commission, and Tsinghua University, who provided valuable comments for this complex research. Last but not least, we also highly acknowledge the valuable feedback received from energy research colleagues at the semi-annual meetings of the International Energy Agency's Energy Technology Systems Analysis Programme (IEA ETSAP).

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Appendix D1: Technical description of the CGE model

The global CGE model applied in this study can be classified as a a multi-sector, multi-region, recursive dynamic CGE model that covers 22 economic commodities and corresponding sectors, and eight power generation technologies as detailed in Table A1. As a special model feature, the number of modelling regions, both international and within China is highly flexible to allow for a wide range of studies. In this regard 3, 7, or 30 provincial units of China and 1, 3, or 14 international regions could be analyzed consistently, as summarized in Table A2. This CGE model is solved by MPSGE/GAMS (Rutherford, 1999) at a one-year time step. This appendix discusses in the following paragraphs the key technical features of this model to allow for a deeper understanding of associated modelling results.

D1.1 Production

For each sector (j) in region (r), gross output Q_{rj} is produced using inputs of labor (L_{rj}), capital (K_{rj}), energy ($E_{rj} \in Coal_{rj}$, $Coil_{rj}$, $Cgas_{rj}$ and $Celec_{rj}$), and non-energy material (M_{rj}). In some sectors (Cagri, Coal, Coil, Cmin), resource (R_{rj}) is also input. A four-level nested function is used to characterize the production technologies as showed in Figure A1 and Equation (A-1) below.

$$Q_{rj} = LEO_{1rj}\{M_{rj}, R_{rj}, CES_{2rj}[CES_{3va}(K_{rj}, L_{rj}), CES_{3re}(ele_{rj}, CES_{4rj}\langle coal_{rj}, gas_{rj}, oil_{rj}\rangle)]\}$$
(A-1)

Where CES_{krj} is the CES function at the k-th nesting level, the first level, LEO_{1rj}, is Leontief function, and VAE_{rj}, VA_{rj}, E_{rj}, FOS_{rj} are CES composites of value added & energy, value added, energy and fossil energy, respectively.

The following conditions apply in this regard:

- Land inputs are considered only for agriculture sector (Cagr), other resources are considered for crude oil and natural gas extraction (Coil), coal mining (Coal) and other mining (Cmin) sectors;
- Within energy transformation sectors such as oil refining (Cpet), gas manufacturing (Cgas), primary energy commodities are considered as material inputs;
- The power sector is modelled by three fossil-firing (coal, gas and oil) and five non-fossil (nuclear, hydro, wind, solar and biomass) technologies (Figure A1b). The energy bundle is not combined with capital for fossil-firing technologies, but linked directly to activity output. This means that electricity output is in a linear relationship with energy inputs.

Labor is assumed to be fully mobile across industries within a region but immobile across regions. The mobility feature of capital follows a putty-clay approach, which means that vintage capital is immobile across either regions or industries while new investment is fully mobile across industries within a region.

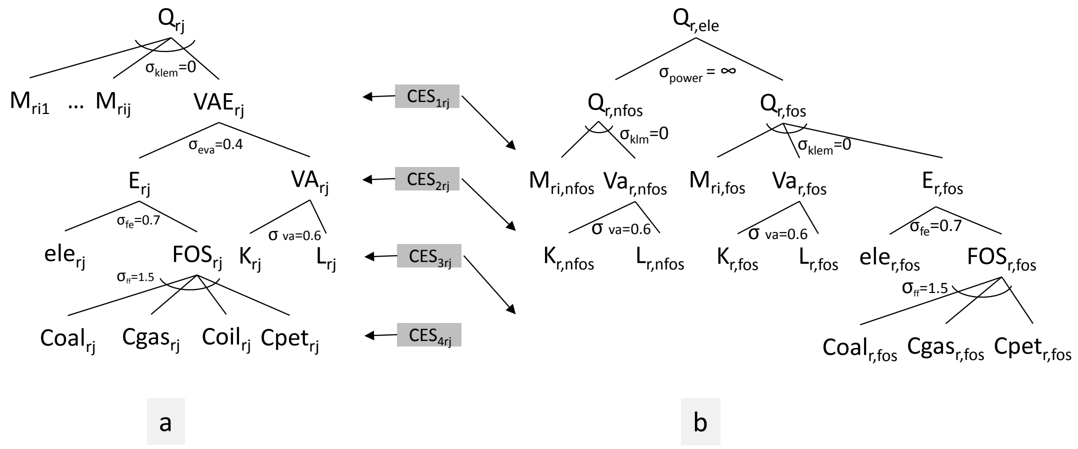

Figure A 1: Nesting of production structure: a, except for electricity sector; b, electricity sector. σ is elasticity of substitution for inputs

A1.2 Final demand

Household and government sectors are represented as two different final consumers. As Equation (A-2) shows, the representative household receives income from the rental of primary factors ($\sum_{f=1}^{F} \omega_{r,f} \cdot V_{r,f} + \sum_j pld_r \cdot QLAND_{r,j} + \sum_{res,j} p_{r,j}^{res} \cdot QRES_{r,j}$) and lump-sum transfer from the government. The income net of direct tax (T_r^d) is used for either investment (or saving, S_r^p) or final consumption ($\sum_i p_{r,j}^q \cdot X_{r,i}^p$). Households maximize their utility by choosing the levels of final consumption of commodities, subject to the constraints of their income and commodity prices (see the income balance in Equation (A-2) below). Total investment is assumed exogenously by Equation (A-9). On the other hand, the government collects taxes ($T_r^d + \sum_j T_{r,j}^z + \sum_j T_{r,j}^m$) and spends the tax revenue in providing public services ($p_{r,i} \cdot x_{r,i}^g$) as explained in Equation (A-3). Although carbon tax (T_r^{cab}) is collected by the government, the model assumes that the revenue from carbon tax is recycled to the household sector as a lump-sum transfer. The demands (DEM_r^d) of household consumption, investment goods and government are specified using Cobb-Douglas utility or demand functions (see Equation (A-4) below).

$$\sum_{f=1}^{F} \omega_{r,f} \cdot V_{r,f} + \sum_j pld_r \cdot QLAND_{r,j} + \sum_{res,j} p_{r,j}^{res} \cdot QRES_{r,j} + T_r^{cab} - T_r^d = \sum_i p_{r,i} \cdot X_{r,i}^p + S_r^p \qquad \text{(A-2)}$$

$$T_r^d + \sum_j T_{r,j}^z + \sum_j T_{r,j}^m = \sum_i p_{r,i} \cdot X_{r,i}^g + S_r^g \qquad \text{(A-3)}$$

$$DEM_r^d = \alpha_r^d \cdot \prod_i \left(X_{ri}^d\right)^{\delta_{ri}}, d\epsilon(household, investment\ and\ government) \qquad \text{(A-4)}$$

Where $\omega_{r,f}$ is price of the f^{th} primary factor, $V_{r,f}$ is f^{th} primary factor endowment by household, pld_r is land price and $QLAND_{r,j}$ is land, $p_{r,j}^{res}$ is price of resource and $QRES_{r,j}$ is quantity of resource, T_r^{cab} is carbon emission tax revenue, T_r^d is direct tax, S_r^p is household savings, $T_{r,j}^z$ is production tax, $T_{r,j}^m$ is import tariff, S_r^g is government savings, $p_{r,i}$ is commodity price, $X_{r,i}^p$ and $X_{r,i}^g$ are commodity final consumption by households and government, respectively.

A1.3 Commodity supply and inter-regional trade

Supply of commodity adopts Armington assumption (Armington, 1969), assuming that goods produced from other provinces and abroad are imperfectly substitutable for domestically and locally produced goods. This approach is shown in Figure A2 and Equations (A-5) and (A-6) below.

Supply to international region (f)

$$X_{fi} = CES_{s1}\{D_{ffi}, CES_{s2}[F_{1fi}, \dots, F_{f'fi}, CES_{s3}(P_{1fi}, \dots, P_{pfi})]\} \qquad \text{(A-5)}$$

Supply to China province (p)

$$X_{pi} = CES_{s1}\{F_{1pi}, \dots, F_{fpi}, CES_{s2}[D_{ppi}, CES_{s3}(P_{1pi}, \dots, P_{p'pi})]\} \qquad \text{(A-6)}$$

Where X_{fi} and X_{pi} are commodities supplied to international region (f) and China province (p), respectively. CES_{sk} is the CES function of supply at k-th nesting level. D_{ffi} is the domestic supply of region f, D_{ppi} is local supply of p, $F_{f'fi}$ is import from other international regions f' to region f, F_{fpi} is import from international regions f to province p, P_{pfi} is import from province p to region f, and $P_{p'pi}$ is inflow of province p from other provinces p'.

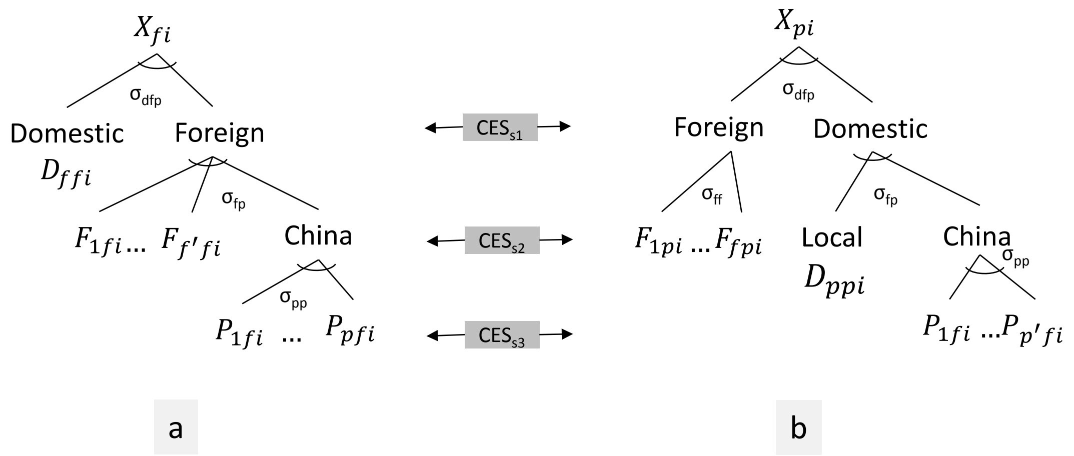

Figure A 2: Aggregation of local, domestic and foreign varieties of good for: a, international regions; b, China provinces. σ is elasticity of substitution for inputs

A1.4 Market clearance

The market-clearing conditions hold for both commodity and factor markets.

For the commodity markets described in Equation (A-7), output Q_{ri} in the corresponding sector j (i=j) is equal to the total demand of intermediate inputs, household, investment and government ($\sum_d X_{ri}^d$), plus export to other international regions ($\sum_f F_{rfi}$) and provinces ($\sum_p P_{rpi}$), minus import from other international regions $\sum_f F_{fri}$ and provinces ($\sum_p P_{pri}$), and plus stock change (STK_{ri}):

$$Q_{ri} = \sum_d X_{ri}^d + \sum_f F_{rfi} + \sum_p P_{rpi} - \sum_f F_{fri} - \sum_p P_{pri} + STK_{ri} \qquad \text{(A-7)}$$

For the factor markets described in Equation (A-8), supply of total factor (V_{rf}) is equal to factor inputs in all sectors (v_{rfj}):

$$V_{rf} = \sum_j v_{rfj} \quad \text{(A-8)}$$

A1.5 Macro closure

In a CGE model, the issue of macro closure is the choice of exogenous variables, including macro closure of investment-saving balance and current account balance. In this CGE model, government savings (S_r^g), total investment and balanced of payment are fixed exogenously, and foreign exchange rate is an endogenous variable.

A1.6 Dynamic process

The model is solved at one-year time step in a recursive dynamic manner, in which the parameters of capital stock (Equation (A-9) and (A-10)), labor force (Equation (A-11)), land, natural resource, efficiency (Equation (A-12)), and extraction cost of fossil fuels are updated based on the modelling of inter-temporal behavior and results of previous periods.

Capital accumulation process:

$$I_{r,\mathrm{tot,t+1}} = \sum_j CAPSTK_{r,j,t+1} \cdot \left[\left(1 + g_{r,t+1}\right)^T - (1 - d_r)^T\right] \quad \text{(A-9)}$$

$$CAPSTK_{r,j,t+1} = (1 - d_r)^T \cdot CAPSTK_{r,j,t} + T \cdot I_{r,\mathrm{i,t}} \quad \text{(A-10)}$$

Where total investment ($I_{r,\mathrm{tot,t}}$) is given exogenously, investment in sector j ($I_{r,\mathrm{j,t}}$) is determined by the model depending on the rate of return to capital, capital stock accumulation ($CAPSTK_{r,j,t}$) follows Equation (A-10), d_r is the depreciation rate (5% for all regions), and T is time step (1 year),

Supply of total labor, land and resource:

$$\mathrm{F}_{r,pf}^t = \mathrm{F}_{r,pf}^{t-1} \cdot (1 + gr_{r,pf}^t) \quad \text{(A-11)}$$

Where $\mathrm{F}_{r,pf}^t$ is primary factor (*pf*) of labor force, land and resource, and $gr_{r,pf}^t$ is the corresponding exogenous growth rate.

Efficiency parameters:

The CGE model distinguishes technological efficiency improvement of new investments from that of existing capital stock.

For new investments, sectoral efficiencies of energy, land productivity and total factor productivity are given as exogenous scenarios, while for existing capital stock, efficiency of *par* (par ∈efficiency of energy and capital) in time t ($\mathrm{EFF}_{r,par,j}^{ext,t}$) is the average of capital stock ($\mathrm{EFF}_{r,par,j}^{ext,t-1}$) and new investments ($\mathrm{EFF}_{r,par,j}^{new,t-1}$) in the previous period, as per Equation (A-12) here:

$$\mathrm{EFF}_{r,par,j}^{ext,t} = \frac{\left(\mathrm{EFF}_{r,par,j}^{ext,t-1} \cdot CAPSTK_{r,j,t-1} + \mathrm{EFF}_{r,par,j}^{new,t-1} \cdot I_{r,\mathrm{j,t-1}}\right) \cdot (1 - d_r)^T}{CAPSTK_{r,j,t}} \quad \text{(A-12)}$$

A1.7 Data

Most of the global data in the CGE model are based on GTAP 6 (Dimaranan and V., 2006) and IEA (IEA, 2009). China-specific provincial data sources are the 2002 inter-regional input-output tables (IOT) (Li, Qi et al., 2010) and the 2002 energy balance tables (EBT) (NBS, 2003). In addition, carbon emission factors; energy prices for coal, oil and gas; and renewable energy technology costs are also required. All the datasets are currently converted to the base year of 2002. Moreover, it is well known that IOT and EBT are inconsistent when it comes to energy consumption across sectors, and the energy data from EBT is regarded as more reliable than IOT. A novel characteristic of this CGE model is that the IOT of China is consistent with the sectoral energy consumption from China's EBT. In order to achieve this consistency, we used the linear least square method, as described in equations (A-13) - (A-16) below:

Minimizing:

$$\varepsilon = \sum_{en,i} \left(Shr_{en,i}^{IOT} - Shr_{en,i}^{EBT} \right)^2 \tag{A-13}$$

Subject to:

$$Shr_{en,i}^{IOT} = \frac{EN_{en,i}^{IOT}}{TCON_{en}^{IOT}} \tag{A-14}$$

$$Shr_{en,i}^{EBT} = \frac{EN_{en,i}^{EBT}}{TCON_{en}^{EBT}} \tag{A-15}$$

$$\sum_i EN_{en,i}^{IOT} \times P_{en} = \sum_i EN_{en,i}^{EBT} \tag{A-16}$$

Where

ε	Error to be minimized
en	Energy commodities (coal, gas, oil, electricity)
i	Sector classification in Table A1
$Shr_{en,i}^{IOT}$	Share of energy consumption across sectors in IOT (%)
$Shr_{en,i}^{EBT}$	Share of energy consumption across sectors in EBT (%) according to (NBS, 2008)
$EN_{en,i}^{IOT}$	Energy consumption of *en* in sector i in IOT (USD)
$EN_{en,i}^{EBT}$	Energy consumption of *en* in sector i in EBT (PJ)
$TCON_{en}^{IOT}$	Total energy consumption of *en* in IOT (USD)
$TCON_{en}^{EBT}$	Total energy consumption of *en* in EBT (PJ)
P_{en}	Price of energy *en* (USD/PJ)

Table A 1: Classification of 22 sectors and 8 power technologies

Nr	Code	Note	Nr	Code	Note
1	CAgri	Agriculture (need land input)	16	CMetPrd	Metal product
2	Coal	Coal (need resource input)	17	Celec	Electricity
3	Coil	Crude oil and natural gas (need resource input)	i	eCoa	Coal power
4	Cmin	Other Mining (need resource input)	ii	eOil	Oil power
5	CFdTbc	Food and Tabaco	iii	eGas	Gas power
6	CTxt	Textile	iv	eHyd	Hydro power
7	Cpaper	Paper	v	eNuc	Nuclear power
8	Cpet	Petrol oil	vi	eWnd	Wind power
9	Cchem	Chemicals	vii	eBio	Biomass power
10	CNonMPrd	Non-Metal product	viii	eSol	Solar power
11	CMetSmlt	Metal smelting and processing	18	CGas	Manufactured
12	CMchn	Machinery	19	Cwater	Water production
13	CTspEq	Transport equipment	20	CCnst	Construction
14	CElcEq	Electronic equipment	21	CTrsp	Transport
15	COthManuf	Other manufacturing	22	Csvc	Service

Table A 2: Model regions defined in the CGE model – Options for China regions and international regions

China regions			**International regions (excl. China)**	
30 provinces in China	**3 China-Regions**	**7 China-Regions**	**14 International Regions**	
Beijing	East	North China	AFR	Africa
Tianjin	East	North China	AUS	Australia-New Zealand
Hebei	East	North China	CAN	Canada
Shanxi	Central	North China	CSA	Central and South America
Inner Mongolia	West	North China	EEU	Eastern Europe
Liaoning	East	Northeast China	FSU	Former Soviet Union
Jilin	Central	Northeast China	IND	India
Heilongjiang	Central	Northeast China	JPN	Japan
Shanghai	East	East China	MEA	Middle East
Jiangsu	East	East China	MEX	Mexico
Zhejiang	East	East China	ODA	Other Developing Asia
Anhui	Central	East China	SKO	South Korea
Fujian	East	East China	USA	United States
Jiangxi	Central	Central China	WEU	Western Europe
Shandong	East	East China		
Henan	Central	Central China	**3 International Regions**	
Hubei	Central	Central China	NON-OECD	Non-OECD countries
Hunan	Central	Central China	OECD	OECD countries
Guangdong	East	South China	BRICS	Brazil, Russia, India and South Africa
Guangxi	West	South China		
Hainan	East	South China	**1 International Region**	
Chongqing	West	Southwest China	ROW	Rest of the world
Sichuan	West	Southwest China		
Guizhou	West	Southwest China		
Yunnan	West	Southwest China		
Shaanxi	West	Northwest China		
Gansu	West	Northwest China		
Qinghai	West	Northwest China		
Ningxia	West	Northwest China		
Xinjiang	West	Northwest China		
Tibet	West	Southwest China		

Appendix D2: Technical description of TIAM

TIAM classification and historic development

TIAM (TIMES Integrated Assessment Model) is a highly detailed, technology-rich global TIMES model. It belongs to a family of bottom-up MARKAL and TIMES models, which are supported by the Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency (IEA) since 1976. The model's structure was adopted from the MARKAL-based SAGE model of the US Department of Energy's Energy Information Administration (US DoE EIA). SAGE was previously used for the US DoE EIA's International Energy Outlook. Within TIAM the world is usually divided into 15 model regions and the time horizon is 2100, which is needed for long-term climate mitigation policies. TIAM is well documented in its TIMES code and application areas in (Loulou, Remme et al., 2005, Loulou and Labriet, 2008, IEA, 2013). TIAM's structure is similar to the structure of many national ETSAP-TIMES models, with a focus on the upstream energy sector and energy commodity trade.

TIAM application for a sub-regional analysis of China (this study)

In this study, TIAM was expanded further in its modelling regions in order to represent a more detailed, sub-regional energy system of China. For this purpose, Chinese national and provincial energy statistics were collected, evaluated and integrated in the model. In order to ensure comparability of China's sub-regions with other model regions, a new methodology to construct the regional energy balances in China in standardized international units was developed specifically for this study (Mischke, 2013). The TIAM model applied in this study has therefore 17 model regions and an expanded China-specific database. Furthermore TIAM drivers for energy service demand for all model regions were reviewed and updated in a joint soft-linking exercise discussed in Chapter D-3. While various TIAM models are developed for specific applications, such as the TIAM model with additional regional China features used in this study, the core structure and database of the TIAM model is maintained and continuously updated in an open-source philosophy under IEA ETSAP.

TIAM optimization framework

TIAM is driven by a set of demands for energy services in the agriculture, residential, commercial, industry, and transportation sectors. The construction of the baseline scenario for energy services is done via global general equilibrium models, such as the CGE model used in this study, and coherent global socio-economic assumptions, such as the SSP2 scenario in this study.

For each new run, TIAM simultaneously recalculates, amongst others, demands for energy services; energy produced and consumed; energy prices; GHG emissions; emission prices, and technology use. Physical quantities and prices are in equilibrium over all sectors, periods in the horizon, and modelling regions. The equilibrium maximizes total suppliers and consumers surpluses via Linear Programming. In this regard, the underlying objective function in TIAM minimizes the discounted sum of annual costs (including investment costs, operation and maintenance costs, surveillance and decommissioning costs, costs for material inputs during construction, taxes) minus revenues (such as subsidies and revenues from recuperated materials) under user-specified policy constraints (such as a policy target to abandon nuclear power in a future year). TIAM is thus choosing an optimal mix of technologies to invest in and operate in a model region at each future period specified.

TIAM structure: reference energy system, technologies and energy resources

Based on energy balance tables, energy sector studies, and other energy statistics for a model region, TIAM constructs a coherent image of an existing energy system (so-called reference energy system). The energy system is represented as a network of energy flows, from resource extraction and indigenous supply to five core end-uses in industry, transport, commercial and public services, households and agriculture. These five core sectors are made up of several subsectors, for example industry includes iron and steel, chemical, non-metallic minerals, pulp and paper as major energy intensive sectors. Modelled energy commodities include coal and coal products (mainly modelled as hard coal), oil and petroleum products (mainly modelled as crude oil in supply, then later many different petroleum products from refineries), natural gas including LNG, electricity from various sources, heat and biomass (including waste, straw, crops stalks as supply, biogas and biofuels in transformation and end use).

A technology may represent any process that produces, transforms, conveys, and/or consumes energy and/or emissions (and some materials). It is characterized by several technical and economic parameters and by emission coefficients for various green-house gases, including CO_2, CH_4, and N_2O. Such technological detail allows precise tracking of capital turnover. This underlying structure allows a more precise bottom-up description of technological competition than feasible in top-down models.

Primary resources are disaggregated by type (e.g. proven vs. future natural gas reserves, connected vs. not, frontier gas, CBM, associated gas, etc). Each type of non-renewable resource is described in each region by means of a step-wise supply curve for the cumulative amounts in the ground, technical annual extraction limits, and fixed and variable costs, thus constituting a compound step-wise supply curve for each primary energy form (coal, oil, gas). All renewable energy forms have annual potentials in each region, also with multiple steps.

The TIAM time horizon until 2100 is usually divided into periods of 10-year duration, which represent an average year. Apart from the time-periods in years, the TIAM models also include user-defined time divisions called time-slices within each year. The use of time-slices is important for commodities that have significant variation in their production and demand at different times of the year, thereby affecting the price of the commodity. The commodities for which time-sliced modelling is applied include electricity, heat and other non-storable energy forms. There are usually six sub-annual time-slices defined in TIAM.

TIAM also includes climate equations to calculate GHG concentrations in the atmosphere and the oceans, the consequential changes in radiative forcing, and hence changes in global mean temperature.

Supplementary Material: Calculation results

The supplementary material provides the results of all our model calculations in EXCEL tables. We welcome further research based on the data set developed in this study.

Global energy perspectives with an emphasis on wind energy

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Book chapter

1st November 2014

Published by the Technical University of Denmark as part of the DTU International Energy Report 2014

"Wind energy – drivers and barriers for higher shares in the global power generation mix"

ISBN: 978-87-550-3969-8

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Tables and Figures

E.1. Introduction

This chapter gives an overview of the current status of wind power globally and the growth in installed wind capacity over the last decade. It reviews global projections of wind power growth in scenarios from various energy system models, and draws conclusions about the necessary conditions to scale-up wind energy in the future.

The future role of wind in the global energy mix was assessed from a number of energy modelling scenarios conducted by leading energy industry, research and international organizations. These include the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), the International Institute of Applied Systems Analysis (IIASA), the Global Wind Energy Council (GWEC), Exxon Mobile and the US Department of Energy (US DoE). We compare a number of global energy scenarios involving different levels of ambition for future GHG targets to see how big a role wind power is expected to play. We then showcase estimates for the future realisable global and regional potential of wind power from IRENA's recent renewable energy roadmap study (REmap) to 2030, which is based on inputs from a wide range of country experts and stakeholders.

E.2. Global wind power: current status

Wind power installations globally have grown at around 25% a year since 2000. Wind has provided almost one third of global renewable power sector capacity additions during 2001-2013 (IRENA, 2013). Global installed wind capacity at the end of 2013 was around 320 GW, including about 310 GW onshore installations (Figure E-1). Less than 2% of current global wind capacity is installed offshore (Figure 2).

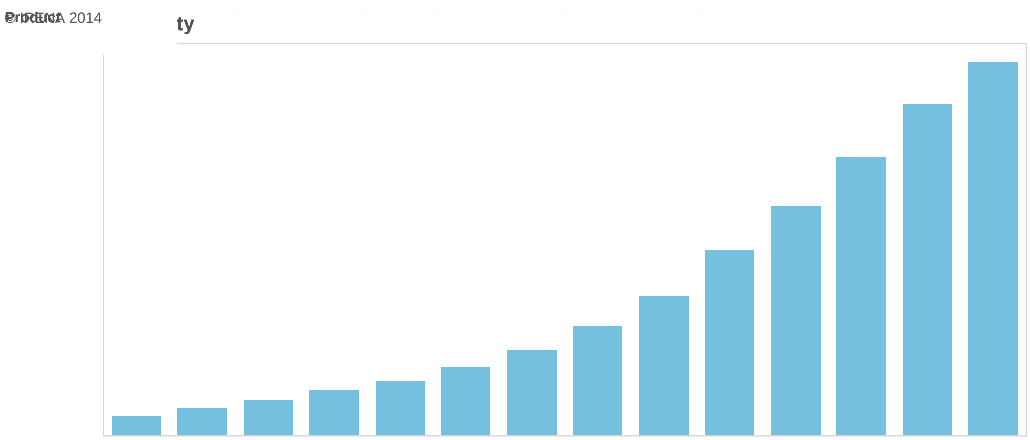

Figure E-1: Growth of global installed wind capacity, 2000-2013 (IRENA).

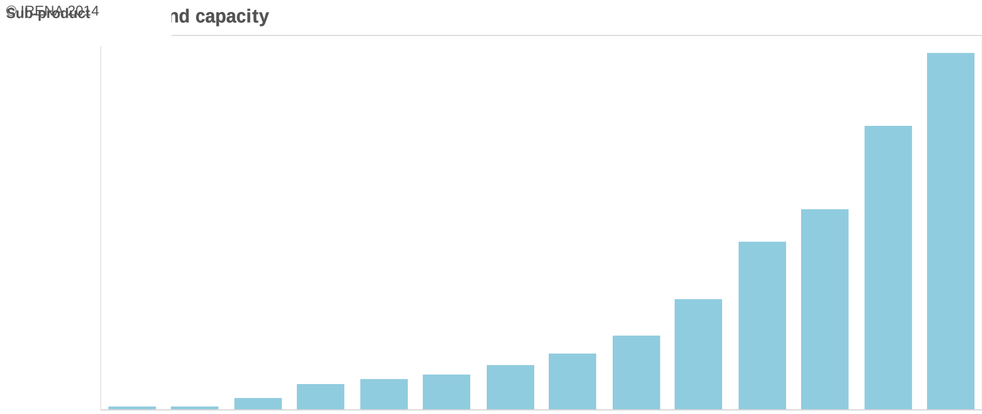

Figure E-2: Growth of global installed offshore wind capacity, 2000-2013 (IRENA).

The regions with most installed wind capacity today are China, the US, India and Europe. These are also the regions with the fastest growth in installed capacity (Figure 3). Onshore wind installations were concentrated in China, followed by the EU and the US, whereas offshore wind installations were concentrated in the EU, mainly in the UK, Denmark, Germany, and Belgium.

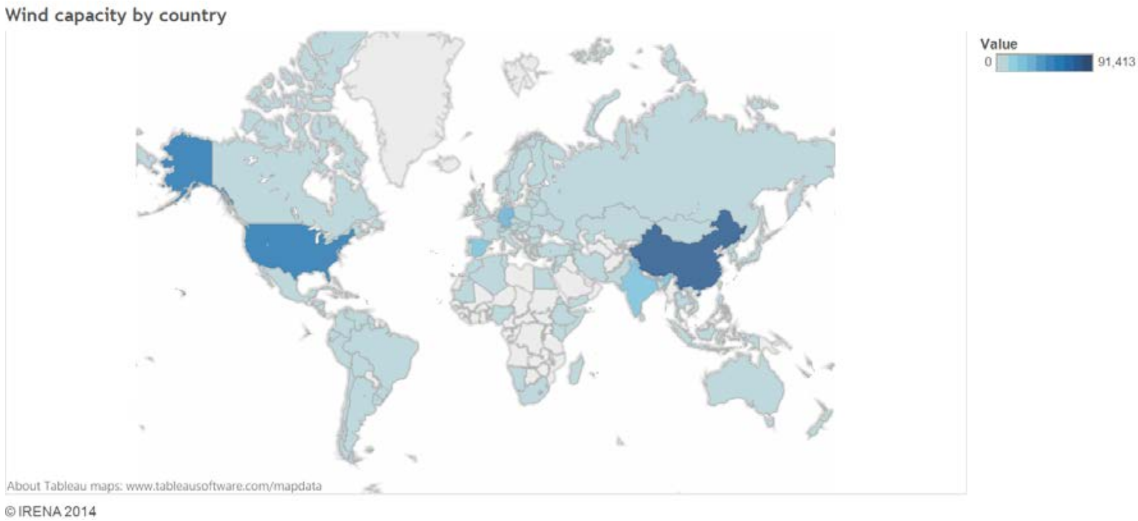

Figure E-3: Regional distribution of total (top) and offshore (bottom) wind capacity in 2013 (IRENA).

E.3. Wind power: Evaluating global projections towards 2050

To investigate what role wind energy can play at a global scale, we have reviewed the role of wind power in scenarios derived from global energy system models produced by leading energy industry, research and international organisations. Their various projections for wind power towards 2050 show a wide range: from a conservative 2500 TWh/y to an optimistic 14000 TWh/y. The most progressive global wind power projections discussed here are published by Greenpeace, the Global Wind Energy Council and IRENA. The most conservative global wind power projections are presented by Exxon Mobile and the US Department of Energy. Table 1 summarises the main assumptions behind these scenarios and ranks them with regard to their ambition for the role of wind power in 2050.

The institutions and organisations referred in Table E-1 often present several scenarios under different framework conditions and assumptions. Where there is a choice, we show the most ambitious GHG reduction scenarios with the most optimistic assumptions for wind power – a decision which underlines the purpose of this chapter, which is to illustrate how big a role wind power can play in the future global power system if development favours it. In order to provide a deeper understanding of an optimistic global wind power scenario, we focus more in depth on the recent IRENA renewable energy roadmap (REmap 2030) in the next paragraph.

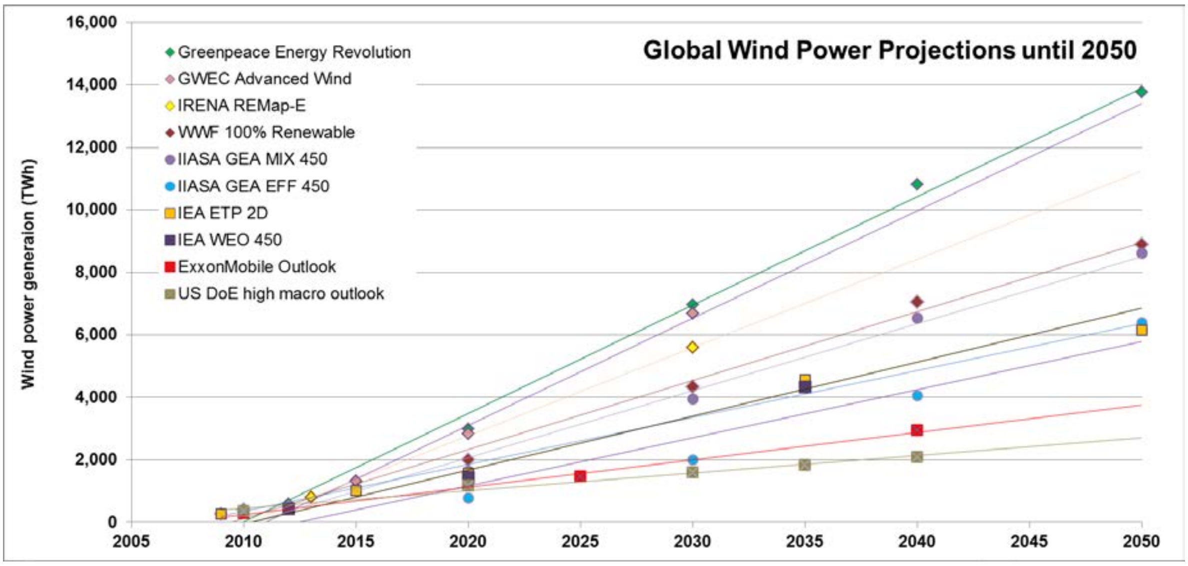

Figure E-4: Global wind generation up to 2050, as projected by ten different institutions (DTU).

Ranking of wind power projections	Organization; Year of Study	Main scenario assumptions
Most progressive	**Greenpeace; 2012**	**Greenpeace Energy Revolution scenario** - goal of 100% renewable power by 2050 - strong political commitment and international cooperation to keep global mean temperature rise below 2°C and a carbon price of $75 /tonne - hybrid/electric cars will predominate in 2050 and nuclear energy will be phased out
	Global Wind Energy Council (GWEC); 2013	**Advanced Wind Scenario of the Global Wind Energy Outlook** - electricity demand is based on the IEA's World Energy Outlook and projected to increase from 15000 TWh in 2005 to 29,000 TWh in 2030 - current international renewable energy and CO_2 targets will be met - most ambitious vision to develop the full potential of global wind turbine manufacturing
	International Renewable Energy Agency (IRENA); 2014	**REmap-E (electrification) Case** - based on SE4ALL targets, country based renewable and efficiency targets, including doubling of the global renewable energy share by 2030 - increased electrification in energy end-use would create additional demand that would be met by mainly wind power - wind capacity would increase to 2050 GW by 2030, with total production of 5600 TWh/y
	World Wildlife Fund (WWF); 2011	**100% Renewable scenario** - goal of 100% renewable energy by 2050 - final energy consumption will peak in 2020 and then decrease to 261.4 EJ in 2050, down from 327.7 EJ in 2010 - electrification in various sectors; in industry, the share of renewables will increase from 8% in 2010 to 79% in 2050; new buildings will be near-zero-energy by 2030; modal shift from fuel to electricity in the transport sector
	International Institute of Applied Systems Analysis (IIASA); 2012	**MIX 450 ppm scenario of the Global Energy Assessment** - scenario analysis with the bottom-up, technology-rich global MESSAGE integrated assessment model - critical social and environmental goals are met, such as stabilising global mean temperature rise at 2°C, enhancing energy security through diversification of the energy supply, and attaining universal access to modern energy services by 2030 - primary energy demand is expected to reach 700 EJ in 2050, up from 490 EJ in 2005 - renewables will represent approximately 75% of primary energy by 2050 - Mix pathway emphasising regional diversity at an intermediate level combined with advanced transport technologies
	International Energy Agency; 2012	**2 degree scenario of the Energy Technology Perspectives 2012** - scenario analysis with a bottom-up, technology-rich global TIMES optimisation model - deployment of a low-carbon energy system, 80% chance of limiting global mean temperature rise to 2°C (consistent with IEA WEO 450 scenario) - global primary energy demand will increase by 37% between 2009 and 2050 - oil is partially replaced by a portfolio of three alternative fuels: electricity, hydrogen and biofuels
	International Energy Agency; 2013	**450 ppm CO_{2eq} scenario of the World Energy Outlook** - based on the IEA's World Energy Model, which replicates the dynamics of energy markets using historical data on economic and energy variables to generate projections - global primary energy demand will increase by 35% between 2010 and 2035 - 80% chance of limiting mean global temperature increase to 2°C
	International Institute of Applied Systems Analysis (IIASA); 2012	**EFF 450 ppm scenario of the Global Energy Assessment** - scenario analysis with the bottom-up, technology-rich global MESSAGE integrated assessment model - critical social and environmental goals are met, such as stabilising global mean temperature rise at 2°C, enhancing energy security through diversification of the energy supply, and attaining universal access to modern energy services by 2030 - primary energy demand is expected to reach 700 EJ in 2050, up from 490 EJ in 2005 - renewables will represent approximately 75% of primary energy by 2050 - efficiency pathway emphasising demand side and efficiency improvements combined with advanced transport technologies
	ExxonMobil; 2014	**Global Energy Outlook** - scenario analysis based on Exxon Mobil Corporation's internal estimates of energy demand, supply, and trends through 2040, plus external sources including the IEA - global demand for energy is projected to rise by about 35% from 2010 to 2040 - energy intensity will decrease by almost 45%; the share of fossil fuels in world energy demand will remain at nearly 78%
Most conservative	**US Department of Energy (US DoE); 2013**	**High macro scenario of the International Energy Outlook** - projections are generated from the EIA's World Energy Projection Plus (WEPS+) model - high macro-economic growth globally: 3.4% annually on average from 2008 to 2035 - world total energy consumption will increase by 53% from 2008 to 2035 - energy intensity will decline by just under 40% from the 2008 level; the price of oil is $125 per barrel in 2035; electricity generation will increase by nearly 84%

Table E-1: Global wind energy scenarios from different leading energy institutions – ranking with respect to wind power projections (DTU).

E.4. Wind power projections: Insights from IRENA's renewable energy roadmap towards 2030

IRENA has developed a global renewable energy roadmap (REmap) that aims to double the share of renewables in the global energy mix by 2030. Known as REmap 2030, the roadmap was created through collaboration between IRENA, national experts within individual countries, and other stakeholders. The IRENA REmap project shows how much wind power we can expect by 2030 with the policies that have already been implemented, and what could be achieved with new policies according to the REmap 2030 roadmap. This renewable energy roadmap is based on separate estimates from each region, without taking global synergies into account, and is focused on achieving a doubling of renewable energy, not necessarily a lowest cost energy pathway; however it shows that in general wind power is cost-effective when compared to convention generation sources.

The aspirational target for REmap 2030 derives from the United Nations Sustainable Energy for All (SE4All) initiative. REmap 2030 is a global gap analysis built on a collective study of major energy-consuming countries. For the country analysis, existing national energy master plans, RE policy goals and targets were used to establish a reference case predicting the energy mix and power supply mix in 2030. Under this reference case, the share of renewables in world total final energy consumption would increase from 18% in 2010 (half of which is accounted for by traditional uses of biomass) to 21% in 2030. Government-nominated country experts (REmap experts) and IRENA subject experts then identified additional options for deploying renewable energy beyond the reference case, and assessed their costs.

REmap explored different ambitious renewable energy cases which would achieve higher shares than the reference case. Up to 36% of renewable energy, measured in terms of total final energy consumption (TFEC) by 2030 is projected when renewable energy deployment is combined with universal energy access and improved energy efficiency. REmap 2030 identified in its main case the potential to deploy an additional 660 GW of wind capacity above the reference case, producing 4400 TWh/y from 1630 GW of total capacity by 2030. Wind energy becomes the third-largest renewable energy source (if viewed in final energy terms, which include fuel use in the end-use sectors) in 2030 after biomass and hydro power, and the fourth-largest source of power after coal, natural gas, and hydro. REmap also explored another case in which increased electrification in energy end-use would create additional demand that would be met by renewable power, mainly wind power. This “REmap-E” case would increase wind capacity to 2050 GW, with total production of 5600 TWh/y by 2030. The study shows that the country with the largest expected share of wind energy in its power system in 2030 is Denmark (with over 60% of its electricity from wind), followed by Germany and the UK (40–50%). Further down the league are Australia, France and the US (20%), and then a group that includes China (15–20%).

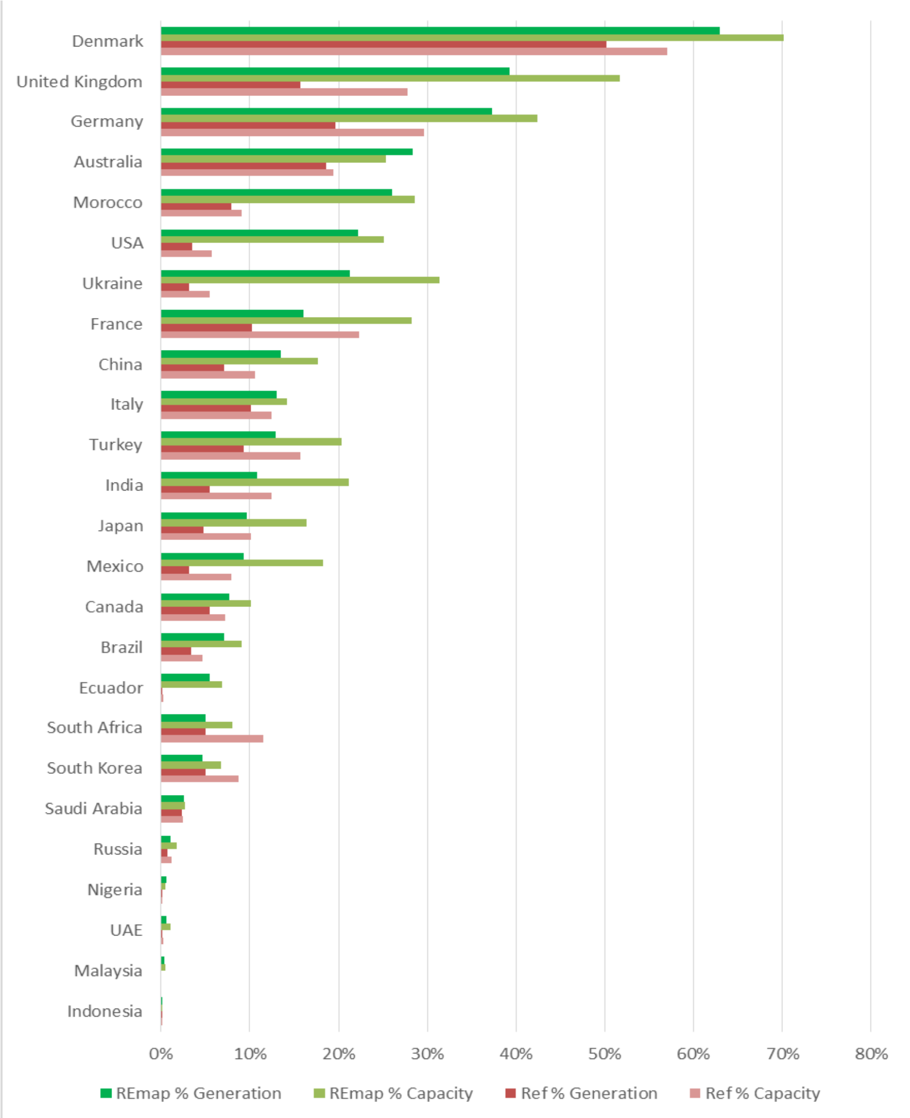

Figure E-5: Wind energy by country in 2030 (installed capacity and generation) as a percentage of total electricity generation, for the reference case (Ref) and for REmap 2030 (IRENA).

E.5. Conclusion: Enabling conditions for scaling-up global wind power

The future role of wind power on a global scale is set to increase further. The level of ambition towards wind electricity generation depends however on many factors and projections from the discussed studies vary considerably. The most optimistic studies for wind energy are based on a strong political commitment for a future low-carbon energy system and assume a global energy transition towards keeping global mean temperature rise below 2°C by 2050.

Progressive wind energy projections assume an installed wind capacity of up to 5000 GW in 2050. This assumes that about 4600 GW wind installations (more than 14 times of the current level) would need to be manufactured, installed and grid-connected globally. Such an expansion of global wind capacity would mean that the wind turbine manufacturing industry would have to be able to build and install about 100 GW/year in 2020, and 200–250 GW/year from 2030 onwards when assuming a 20-year turbine life. The geographical patterns of onshore and offshore wind deployment are projected to diversify, based on country-specific conditions. Considerable additional investments in wind power are needed to implement any ambitious renewable energy scenario. Reaching the wind capacities identified in REmap 2030 would for example require annual investments of $314 billion/y for onshore wind and $47 billion/y for offshore wind.

In summary we identify the following enabling key factors to scale-up wind energy in the future:

- high electricity demand and transition to electricity-based energy systems, for example by increased electrification of the transport sector
- power systems, that are able to handle increasingly higher shares of intermittent power production, such as shown in Denmark
- progressive cost reduction of wind power technologies
- continuous high investments in wind energy, that allow manufacturing and installation of about 100 GW/year globally

Country case study: China – ETSAP-TIAM and AIM/CGE

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Book chapter

Springer Research Series
"Informing energy and climate policies using energy system models - Economic Impacts of Future Changes in the Energy System"

in collaboration with the
International Energy Agency Energy Systems Technology Analysis Program (IEA ETSAP)

under review since January 2015

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Tables and Figures

F.1 Introduction

China's economy and energy system developed rapidly since the 1980s, followed by an increase in CO_2 emissions. Analysing pathways for China's future development and associated global issues relies on complex global modelling tools that incorporate sufficient sub-regional details of China. Recent modelling exercises that account for such global and sub-regional economy and energy system features are however rarely described in the peer-reviewed academic literature (Mischke and Karlsson, 2014).

This China soft-linking case study aims to bridge this knowledge gap between existing global and China-specific scenario studies, which are currently carried out by different academic institutions with multiple modelling tools (Mischke and Karlsson, 2014). One example of a such a modelling exercise for China was carried out by Chen (2005). Using a hybrid MARKAL MACRO model for China, Chen (2005) concluded that the economic costs of a carbon emission reduction pathway in China towards 2050 are rather high, estimated at up to 2.54% of GDP loss.

The soft-linking of a global TD economic model, the Asian-Pacific Integrated assessment Model (AIM/CGE) developed in the National Institute of Environmental Studies of Japan (NIES), with a global BU energy system model, the ETSAP-TIAM model with sub-regional China features developed in the Technical University of Denmark (DTU), is carried out here to establish a common global and China-specific reference scenario. On this basis, global, China national and China sub-regional economic, energy and emission pathways can be documented, analysed, and replicated simultaneously.

F.2 Methods

The two global optimization models are expanded with a sub-regional level of detail for China as per the country's regional geographic definitions of the 7th Five Year Plan (NPC, 1985). Both models represent the economy and energy system of 16 world regions plus China. China-specific base year data are calibrated against official Chinese government statistics, including provincial energy balances and input-output tables. The global AIM/CGE model represents moreover up to 30 provinces of China, with 22 economic sectors and three final demand sectors (Dai, Mischke et al., Forthcoming). A triangulation method to integrate provincial energy statistics for China into ETSAP-TIAM (Loulou and Labriet, 2008) was established (Mischke, 2013).

The soft-linking approach used in this study comprises the following three major steps, which are similar to other country case studies presented here:

1. **Step 1: TD to BU**

The AIM/CGE model provides initial inputs for the ETSAP-TIAM model for a direct or indirect linking of the sectors in both models. The outputs of the economic sectors from the AIM/CGE model are used as drivers for energy service demand in ETSAP-TIAM model. If required, alternative projections from other sources are used, such as population statistics.

2. **Step 2: BU to TD**

After ETSAP-TIAM calculates the optimal technology mix and final energy demand in different sectors, the energy efficiency parameters of the AIM/CGE model are adjusted so that the energy consumption matches the ETSAP-TIAM results.

3. **Step 3: Model iterations**

After these two steps, equivalent to the first iteration, the results of energy service demand in the AIM/CGE model might change. If the change in parameters is significant, new iterations are carried out. The hybrid model developed in this study is named CGE-SL.

Common reference scenario

A common reference scenario is constructed and tested in various iterations. It follows the GDP and demographic trends of a newly developed, moderate Shared Socio-economic Pathways (SSP2) scenario (O'Neill, Kriegler et al., 2013). The SSP2 pathway is downscaled for China, following the principle that the existing socio-economic disparities within China will be narrowed towards 2050. Future GDP growth projections for China and other model regions are thus a main driver in both models. GDP pathways of East-, Central- and West-China are summarised in Table F-1.

Table F-1: Future economic growth increase for sub-regions of China under SSP2 (2005=1)

Region	2005	2010	2020	2030	2040	2050
East-China	1.0	1.5	3.5	6.5	9.8	12.3
Central-China	1.0	1.5	3.9	7.5	12.1	15.8
West-China	1.0	1.5	3.7	7.0	11.1	14.4

F.3 Reference scenario results

At a **global level**, the hybrid model (see Figure 1, marked in green) shows a 2-2.5 times increase in global power production, primary and final energy use and CO_2 emissions towards 2050. The pathway for final energy is thereby highly harmonised between the different modelling tools. The AIM/CGE model and the ETSAP-TIAM model (see Figure F-1, marked in red and blue), if used stand-alone, diverge increasingly in their pathways for global power production, primary energy use and global CO_2 emissions.

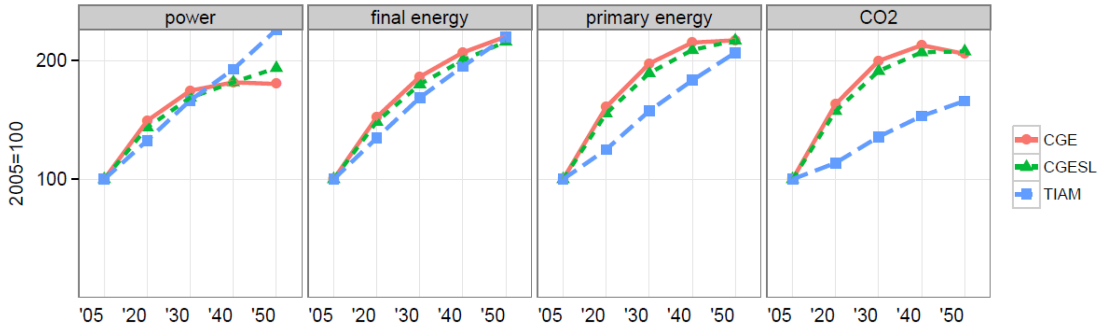

Figure F-1: World reference scenario in TD AIM/CGE, BU TIAM and hybrid CGE-SL models – pathways for power generation, primary and final energy use, and CO_2 emissions towards 2050

At a **China national level**, the hybrid model (see Figure F-2, marked in green) shows a 5 times increase in China's power production, primary and final energy use and CO_2 emissions towards 2050. A peak in these pathways is suggested around 2040 in the TD AIM/CGE and the hybrid CGE-SL model, however not in the BU ETSAP-TIAM model. As described above, the models stand-alone diverge increasingly towards 2050. While the TD AIM/CGE model calculates an almost 6 times increase in all pathways towards 2050, the BU ETSAP-TIAM model calculates a much lower rate of increase of about 3-5 times.

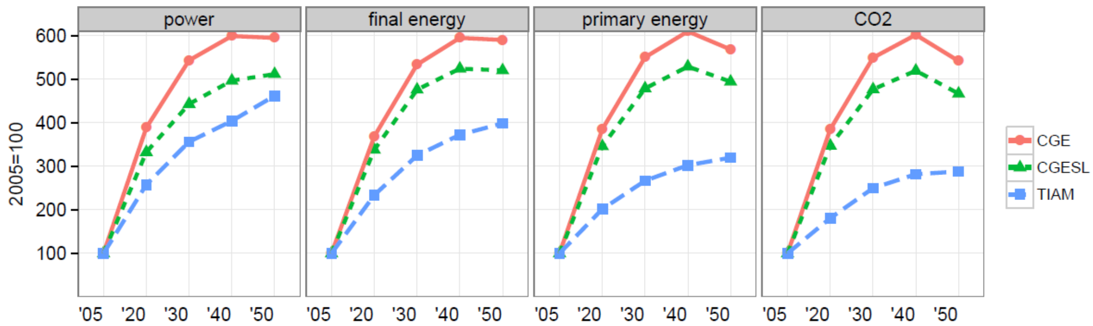

Figure F-2: China reference scenario in TD AIM/CGE, BU TIAM and hybrid CGE-SL models – pathways for power generation, primary and final energy use, and CO_2 emissions towards 2050

Analyzing the modelling results for the **East-China sub-region**, which summarizes the highly developed coastal provinces of China, provides the further insights (see Figure 3). The hybrid CGE-SL model (see Figure F-3, marked in green) shows a 3.5-4 times increase in East-China's power production, primary and final energy use and CO_2 emissions towards 2050. A peak around 2040 is suggested in most pathways studied here, similar to the national-level results for China. As discussed before, the models stand-alone diverge increasingly.

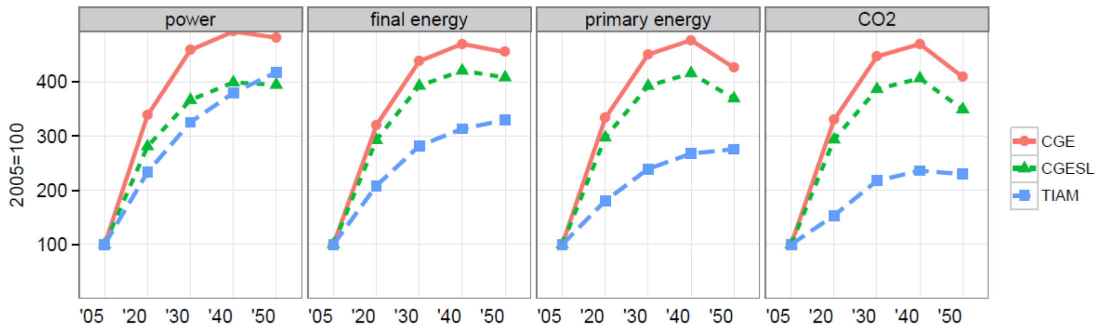

Figure F-3: East-China reference scenario in TD AIM/CGE, BU TIAM and hybrid CGE-SL models – pathways for power generation, primary and final energy use, and CO2 emissions (2005-2050)

The pathways for the **Central-China sub-region**, which comprises many resource-rich provinces of China, are provided in Figure F-4. The hybrid CGE-SL model (see Figure 4, marked in green) indicates a 6-6.5 times increase in Central-China's power production, primary and final energy use and CO_2 emissions towards 2050. The divergence in the pathways of the TD and BU models is highest for CO_2 emissions: the maximum increase in CO_2 emissions between 2005 and 2050 is about 7 times in the TD AIM/CGE model and only about 3 times in the BU ETSAP-TIAM model.

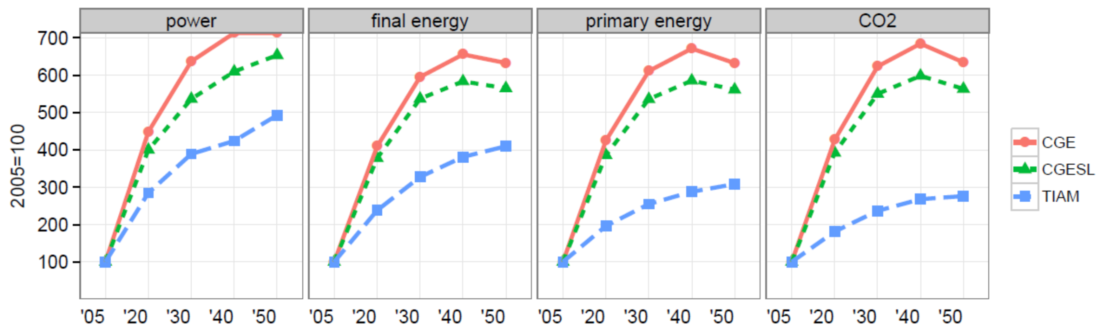

Figure F-4: Central-China reference scenario in TD AIM/CGE, BU TIAM and hybrid CGE-SL models – pathways for power generation, primary and final energy use, and CO2 emissions towards 2050

The **West-China sub-region** comprises many sparsely populated and economically less developed provinces of China. The corresponding future pathways are provided in Figure F-5. The results are similar to the other sub-regions of China, indicating major differences if models are not soft-linked and used stand-alone under a common reference scenario.

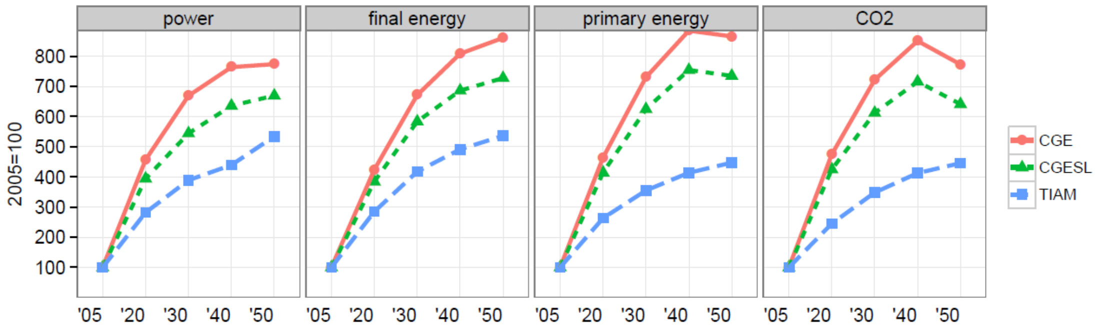

Figure F-5: West-China reference scenario in TD AIM/CGE, BU TIAM and hybrid CGE-SL models – pathways for power generation, primary and final energy use, and CO2 emissions towards 2050

F.4 Discussion

Soft-linking global models with regional China features allows for new, sub-regional insights into China's future economic and energy system development. The common reference scenario established and tested in this study could provide a basis for future scenario studies about the potential global impacts of China-specific sub-regional and national energy and climate policies. These results, if replicable, reliable and transparent, could feed into an ongoing energy and climate policy debate in China, which is striving to balance global and China-specific regional development issues.

As previous scenario studies for China showed, the divergence in China-specific scenario results calculated by different modelling tools with different underlying assumptions is rather high (Mischke and Karlsson, 2014). Our preliminary results confirm that China-specific modelling exercises should be sufficiently harmonised and documented first, before applying any modelling framework to study policy scenarios for China in a global context.

To cope with the range of uncertainty in China's future energy and emission projections, future work should focus on benchmarking such a global and China-specific modelling exercise with more leading global and China-specific scenario studies. More research is also needed to understand and explore uncertainty in underlying statistical differences that serve as inputs for different modelling frameworks.

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Electricity generation costs of concentrated solar power technologies in China based on operational plants

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Journal article

ENERGY

under review since January 2015

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Tables and Figures

Abstract

Recent years witnessed a sharp increase of concentrated solar power (CSP) plants around the world. CSP is currently at its early stage in China, with several demonstration and utility-scale plants underway. China's rising electricity demand, the severe environmental pollution from coal-fired power plants, and favorable renewable energy policies are expected to result in a large-scale CSP deployment in the next years. Detailed CSP studies for China are however hardly available. To fill this knowledge gap, this study collects plant-specific data in a national CSP database in collaboration with local CSP experts. On this basis, this study analysis and benchmarks the costs of parabolic trough CSP, tower CSP, and dish CSP technologies in China by applying a levelized cost of electricity (LCOE) model. The current LCOE for the different CSP plants falls in a range of 1.2-2.7 RMB/kWh (0.19-0.43 US$/kWh). Among the three CSP technology variants discussed, our sensitivity analysis indicates that the tower CSP variant might have the greatest potential in China. We expect a future cost reduction potential of more than 50% and a high share of local content manufacturing for tower CSP.

Keywords
CSP, technology comparison, China, LCOE, thermal storage, renewable electricity generation

Highlights

- First study that analyzes three different CSP technology variants in China.
- First national CSP database for China is compiled, consisting of seven CSP plants under construction and operation.
- LCOE for operational CSP plants is in the range of 1.2-2.7 RMB/kWh (0.19-0.43 US$/kWh).
- Future LCOE for the tower CSP could decline to 0.47 RMB/kWh (0.8 US$/kWh).

Abbreviations

ADB	Asian Development Bank
BIPV	building integrated photovoltaics
BNEF	Bloomberg New Energy Finance
CAS IEE	Chinese Academy of Sciences, Institute of Electrical Engineering
CDB	China Development Bank
CGNPG	China Guangdong Nuclear Power Group
CF	capacity factor
CSP	concentrated solar power
CSPPLAZA	a website of the solar thermal power industry, China
DLR	Deutsches Luft- und Raumfahrtzentrum, German Aerospace Center
DNI	direct normal insolation
ECOSTAR	European Concentrated Solar Thermal Roadmap
EIT	enterprise income tax
FIT	feed in tariff
ESTELA	European Solar Thermal Electricity Association
Gemasolar	a CSP tower plant in Spain
Golden Sun	a national solar photovoltaic program in China
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IRR	internal rate of return
ISEGS	Ivanpah Solar Electric Generating System, a CSP plant in the United States
LCOE	levelized cost of electricity
NDRC	National Development and Reform Commission, China
NEA	National Energy Administration, China
NREL	National Renewable Energy Laboratory, USA
NPV	net present value
O&M	operation and maintenance
PS10	planta solar 10, a CSP tower plant in Spain
RMB	renminbi, Chinese currency, equivalent to Chinese Yuan
US$	US dollar, 2013 average exchange rate used for RMB currency conversions
VAT	value added tax

G.1. Introduction

The Chinese government is increasingly promoting the deployment of renewable energy technologies in order to cope with the country's rising electricity demand and the increasing air pollution and greenhouse gas emissions from fossil-fueled power plants. Concentrated solar power (CSP) plants are considered as one promising renewable-based electricity generation alternative. China's current Twelfth Five-Year Plan for Solar Energy, that was published by the National Energy Administration (NEA) in 2012, includes a 1 GW capacity target for national CSP installations by the end of 2015 [1]. Demonstration projects for all major CSP technologies have been set up in China's provinces and the commercialization of utility-scale CSP plants is starting.

Many studies have evaluated the technical and economic feasibility of different CSP technology variants in various countries worldwide. Electricity generation cost projections for CSP tower and parabolic trough plants in the United States were carried out by NREL, Sargent and Lundy Consulting and Sandia National Laboratories during 2003-2010 [12-14]. The International Energy Agency (IEA) released a CSP technology roadmap in 2010 [15]. The German Aerospace Center (DLR) issued a research report on the potential European technical innovations and research activities for CSP cost reduction in 2005 as part of the EU-funded European Concentrated Solar Thermal Road-Mapping (ECOSTAR) project [16]. The electricity prices and potentials for CSP deployment in Australia [17] and Thailand [18] were also recently discussed in the scientific literature. The International Renewable Energy Agency (IRENA) published a global CSP analysis in 2012 [19], accounting for the most recent CSP research reports and consulting studies published since 2010 [20-24].

To the best of our knowledge, a country-wide technical, economic and financial assessment of different CSP technology variants in China is currently not available. A few plant-specific CSP studies for China were recently published. Li et al. [25] assessed the cost of CSP in China based on a hypothetical CSP parabolic trough plant in 2014. A more realistic study for a 50 MW utility-scale CSP parabolic trough plant in Inner Mongolia, China, was published by the Clinton Foundation in 2013 [26]. A general CSP cost assessment for China is also available in the global IEA report on the projected costs of generating electricity of 2010 [27].

A more comprehensive assessment of CSP technology variants in China is critical for policy makers, energy researchers, and renewable energy industry experts. Therefore this study aims to analyze and benchmark for the first time three different CSP technologies under operation in China. As an expansion of previous studies, this study develops a new national database of seven operational CSP plants in China as of December 2014. First-hand plant-specific data were obtained amongst others through on-site investigations and interviews with local CSP plant operators and domestic energy sector experts. On this basis, this study aims to provide more targeted and detailed insights for future national CSP policies in China, such as a potential CSP-specific feed-in-tariff.

The remaining parts of this study are structured as follows: Section G-2 gives an overview of the current deployment of CSP technologies globally and in China. Section G-3 describes the methodology and underlying assumptions for the levelized cost of electricity (LCOE) calculations for CSP in China. Section G-4 presents the results, including a national database for trough CSP, tower CSP, and dish CSP plants under operation and a LCOE range for CSP in China. Furthermore a sensitivity analysis is carried out to evaluate the future cost reduction potential for CSP. Section G-5 concludes the paper and provides targeted CSP policy recommendations for China. Appendix G-A provides the equations of our LCOE model and appendix G-B lists detailed plant-specific economic and financial data.

G.2. Current status of CSP technology deployment

G.2.1. Global status of CSP technology deployment

By 2013 the global cumulative installed CSP capacity reached 3,483 MW according to the US National Renewable Energy Laboratory (NREL) [2]. Figure 1 shows the annual global thermal CSP capacity from 1985-2013. While the global CSP capacity remained below 450 MW until 2007, a rapid increase in CSP deployment has been taking place in recent years. From 2007 to 2013 the global average annual growth rate of CSP increased to about 139%. Figure 2 shows the cumulative installed capacity of global CSP projects under construction in different countries in 2013, as compiled by the authors from NREL [2] and BNEF [3]. Bloomberg New Energy Finance (BNEF) expects a significant deployment of CSP in the short-term future. Based on the current CSP plants under construction globally, the cumulative commissioned global CSP capacity will reach 6,146 MW by the end of 2015. This would be equivalent to an almost doubling of the global CSP capacity in 2013 [3].

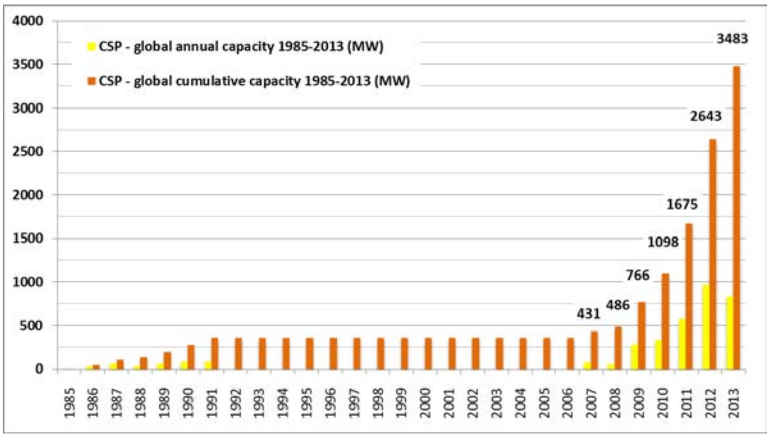

Figure G-1: Global CSP capacity from 1985-2013 - compiled by the authors from NREL [2] and BNEF [3].

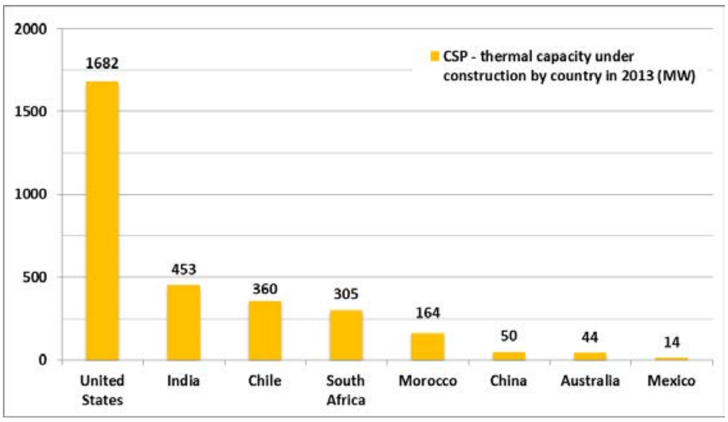

Figure G-2: CSP capacity under construction by country in 2013 - compiled by the authors from NREL [2] and BNEF [3].

Among the CSP plants under operation globally are different CSP technology variants and different project sizes, reaching from small-scale demonstration projects to large-scale utility projects. As shown in Figure 2 above, the United States is currently leading with 1682 MW of CSP under construction, followed by India with 453 MW under construction.

The United States started setting up commercial, utility scale CSP plants since the 1980s. The US Ivanpah Solar Electric Generating System (ISEGS) is currently the world's largest CSP plant. ISEGS has an installed capacity of 392 MW and was put into operation in early 2014 in the Mojave Desert in California [2]. The cumulative installed CSP capacity in Spain reached 2368 MW in 2013, accounting for 68% of the global CSP capacity and ranking second in cumulative CSP installations after the United States. Due to policy changes, no new CSP plants were under construction in Spain by the end of 2013. The parabolic trough CSP technology is the dominant CSP technology in Spain and accounted for about 93% of the country's cumulative installed capacity. Spain is also leading in the CSP tower technology. The first commercial CSP tower plant in Spain started power production in 2007 in Andalucía; it is called planta solar 10 (PS10). The Spanish Gemasolar plant followed in 2011, this CSP tower plant includes a molten salt heat storage system. It is currently the first CSP plant globally that combines a central power receiver with a molten salt heat storage.

Other countries that have operational utility scale CSP plants include India (104 MW), the United Arab Emirates (101 MW), Algeria (25 MW), Morocco (20 MW), Egypt (20 MW) and Iran (17MW); all those are parabolic trough CSP plants [2, 3].

G.2.2. Status of CSP technology deployment in China

By the end of 2013 the installed capacity of commercial CSP in China was about 50 MW, equivalent to one utility-scale CSP plant [2, 3]. The Twelfth Five-Year Plan for Solar Energy includes a planning target of 1 GW of CSP in China [1]. This might seem very ambitious in this context but might also indicate the commitment of the Chinese government to promote CSP in the short-term. No specific policies for CSP were enacted yet in China. Therefore this study mainly is based on renewable and solar PV policies currently enacted in China. Those policies are summarized in the following two paragraphs and are considered in our CSP cost calculations in Section 3.

Renewable energy technologies in China fall under the country's Renewable Energy Law enacted in 2005 [4]. In 2009 an amendment to this law was introduced to further specify the funding support and the obligations for the grid companies to purchase renewable energy [5]. In the same year, two national solar PV programs were started, the Building Integrated Photovoltaics (BIPV) program and the Golden Sun program [6, 7]. A national solar PV feed-in-tariff (FIT) of 1 RMB/kWh (about US$0.16/kWh) was implemented in 2011 and adjusted in 2013 to a FIT range between 0.9, 0.95 and 1 RMB/kWh depending on the solar radiation level in different locations in China. The current solar PV FIT will be in effect for 20 years [8].

Besides the solar PV FIT, a series of financial incentives have also been implemented by the China Development Bank (CDB) and the Ministry of Finance. The CDB has been offering preferential loans for solar PV installations under the Golden Sun Project. NEA in collaboration with CDB announced financial support for distributed solar PV electricity generation in China in August 2013, in particular a 5-10 % discount on interest rates for loan payments. The favorable solar PV loan term has been set at 15 years with an option for extension for another 3-5 years after project-specific evaluation [9]. One month later, the Ministry of Finance issued the Notice for Value Added Tax (VAT) of solar PV electricity generation which guaranteed a reduced VAT rate of 8.5% for solar PV in China, half of the normal VAT [10]. In addition the Enterprise Income Tax (EIT) Law of China entitles new renewable energy companies in China to receive a two-year EIT exemption for their first two profitable years followed by a three-year 50% reduced EIT rate of 12.5% [11].

G.3. Methodology: LCOE calculations for CSP technology variants in China

This study develops and applies a LCOE model to analyze and benchmark the electricity generation costs of different operational CSP plants in China. We first identify and classify all operational CSP plants in China as of December 2014 in a national CSP database. In the next step, a commonly financial model is set up to calculate the costs of generating electricity from the various CSP plants we identified. This is followed by a sensitivity analysis that discusses changes in future cost and technology aspects for CSP in China.

G.3.1. Identification and classification of operational CSP plants in China

CSP technologies are commonly classified in the following four technology variants: (i) parabolic trough CSP, (ii) tower CSP, (iii) dish CSP and (iv) Fresnel reflector CSP [28]. This study analyses and discusses the first three technology variants for China. Considering the relative small-scale application and lack of data for Fresnel reflector CSP plants, this study excluded this CSP technology variant. Since CSP just entered a demonstration phase in China, the plant-specific technical, financial and economic data are difficult to obtain from the literature. This study therefore used on-site expert interviews to collect data for each operational CSP plant in China and to review those with available CSP data reported in the literature.

We develop and apply a project-specific code for each analyzed CSP plant in China to set up a new national CSP database. This code is constructed as follows: we first classify the plant operator, followed by the plant location and subsequently by the specific CSP technology variant. For example the code “CGNPG-Delingha-Parabolic plant” refers to a parabolic trough CSP plant that is operated by the China Guangdong Nuclear Power Group (CGNPG) in Delingha, Qinghai province.

G.3.2. Levelized costs of electricity Model and underlying default assumptions

LCOE models are widely used to evaluate and compare the cost of energy resources. LCOE is commonly defined as "… the constant electricity price that would be required over the life of the plant to cover all operating expenses, payment of debt and accrued interest on initial project expenses, and the payment of an acceptable return to investors” [29]. IRENA used

LCOE as an indicator to evaluate the global cost of CSP and compare CSP costs between countries [19]. Similarly the IEA frequently uses an LCOE model to compare fossil and renewable-based electricity generation costs among countries [28].

This study develops and applies a simple LCOE model to calculate the cost of electricity from different CSP plants in China, accounting for all lifetime costs adjusted for inflation and discounted. The LCOE result for each plant is equivalent to a net present value (NPV) of zero. The detailed equations for the developed LCOE model are provided in appendix A. We use the following necessary economic, financial and technical default assumptions for key parameters in the LCOE model (see table 1 and explanation below). To improve the accuracy and the reliability of the underlying LCOE calculations, this study includes only CSP projects in the LCOE calculations that are already operational and generating electricity as of December 2014.

Table G-1: Assumptions of key parameters in this study.

Key parameter	Unit	Default assumption	Reference to Annex A
Technical parameters			
• direct normal insolation DNI	kWh/(m2 year)	1900	Equation (3)
• capacity factor CF	%	0.22	Equation (3)
Economic and financial parameters			
• debt to equity ratio	%	70 / 30	Equation (4)
• interest rate	%	5.95	Equation (6)
• lifetime	years	25	Equation (3)
• enterprise income tax EIT	%	0% in the first two years; 12.5% in years 3-5; 25% afterwards	Equation (10)
• value added tax VAT	%	8.5	Equation (10)
• surcharge tax	%	17	Equation (10)

<u>Default assumptions for plant-specific technical data</u>

CSP technologies require large quantities of direct normal insolation (DNI) in order to produce electricity and be economically feasible. DNI is a site-specific parameter, that varies in China. In Delingha, Erdos and Wuhai it is about 1800-2000 kWh/ (m^2 year) and about 1900 kWh/(m^2 year) in Yanqing [37]. In order to minimize the influence of DNI variations in our LCOE calculations, this study assumes an average unified annual radiation of 1900 kWh/(m^2 year) for all CSP plants.

The average capacity factor (CF) is another key technical parameter to estimate the lifetime electricity generation of a CSP plant. The 1 MW CAS IEE Yanqing Tower Plant has a capacity factor of about 0.22. The capacity factors obtained for the Datang-Erdos-Parabolic plant was about 0.32 and the one of the Supcon-Delingha-Tower plant was about 0.29. Those two CF are considered as unlikely to be achieved with the current CSP technology and DNI conditions in China, as these are in the range of newly installed CSP plants in the US. The average capacity factor without storage of the ISEGS is 0.3 under an annual solar radiation of 2600 kWh/(m^2 year). Therefore we chose to apply a more conservative capacity factor of 0.22 for all CSP plants in China.

<u>Default assumptions for economic and financial parameters</u>

As stated in section G-2, the economic and financial assessment of CSP will be based on the current solar PV policies in China. We expect in general that the financial expenses for renewable energy projects in China will decrease further in the coming years. With continuing support from the government, more commercial banks are expected to provide loans for renewable energy projects.

We consider that all CSP projects belong to large power companies with financially "strong" balance sheets, allowing for an investment share of 30% in the project's financial structure [38]. The interest rate and the term for loan payments assumed are 5.95% (10% discount rate) and 20 years. This is in line with the current 5-year interest rate set by the People's Bank of China of 6.55% and the 5-10% discounted interest rate for solar PV projects granted by the CDB [9]. We assume different taxes for CSP projects, as follows: With regards to the EIT, the "two-year exemption and three-year half exemption" is applied. The value-added tax (VAT) is set at 8.5%, equivalent to half of the normal level (17%). The VAT paid during the purchase of relevant equipment can be deducted. The study also accounts for a 10% tax surcharge for city construction and 7% education tax [10].

G.3.3. Sensitivity analysis to evaluate the future cost reduction potential for CSP

We carry out two different sensitivity analyses to evaluate the impact of variations in key parameters on the future cost reduction potential for CSP in China, one in a short term perspective and one in a longer term perspective. The future cost reduction potential of the CSP technology variants in the short term assumes a reduced average capacity factor and reduced total investment costs. Additional choices affecting the future CSP costs in China, such as the availability of thermal storage options, are also discussed. Then we evaluate the impact of a potentially important cost changer in the longer term: the availability and cost of thermal storage options. This is considered as a future cost reduction potential of mature CSP technology variants in China.

G.4. Results

We present the results as follows. First we present the first national CSP database for China, which includes the technical, economic, and financial data we collected for the seven different constructed and operational CSP plants. We also map the locations of all discussed CSP plants in different provinces of China. Subsequently we present the results of the current LCOE for the different CSP technology variants in China under the discussed default assumptions. This is followed by a sensitivity analysis of key parameters that are impacting the future cost reduction potential for CSP in China.

G.4.1. National database of CSP plants in China

We identified, collected data, and subsequently analyzed data for seven CSP plants in China, which as of December 2014 have completed the construction phase (and therefore are currently operational and producing electricity) or have received full government approvals and are therefore under construction. All CSP data are summarized in the national CSP database (Table G-2).

A project-specific summary for each of the seven analyzed CSP plant is given below, using the project classification code described in the methodology section before:

CAS IEE-Yanqing-Tower plant
The 1 MW CAS IEE-Yanqing-Tower plant in Beijing is the first CSP demonstration project in China. Its planning, approval and construction took about six years. The plant started generating electricity in 2012 and is fully operational as of July 2013 [39, 40]. The Institute of Electrical Engineering of the Chinese Academy of Sciences (CAS IEE) developed the core tower CSP technology for this plant.

CAS IEE –Yanqing-Parabolic plant
The 1 MW Yanqing Parabolic Trough plant started construction in 2014. It is located near the CAS IEE-Yanqing-Tower plant in Beijing [41]. This demonstration project for parabolic CSP technology was supported by the Chinese 863 R&D project.

Sanhua Heli-Wuhai-Dish plant
The construction of the 1 MW Sanhua Heli-Wuhai-Dish plant located in Wuhai, Inner Mongolia, was completed in October 2013 [42]. A new feature of this plant is the dish design from HelioFocus, which is different from the traditional stirling-dish. Sanhua Group ambitiously plans to increase the capacity of this plant from currently 1W to 200 MW for the second stage in the near future.

Huaneng-Nanshan-Fresnel plant
The 1.5 MW Huaneng-Nanshan-Fresnel plant located in Nanshan, Hainan Province, was put into operation in October 2012. We do not have further information at this stage [43].

Supcon-Delingha-Tower plant
The Supcon-Delingha-Tower plant is the first commercial, utility-scale CSP plant in China. The construction of the first phase with a capacity of 10 MW was completed in January 2013 [44], followed by its grid connection in July 2013 [45]. It is located in Delingha, Qinghai Province, in western China and operated by Supcon.

Datang-Erdos-Parabolic plant
Datang Corporation made a 0.94 RMB/kWh bid for the concession of the parabolic trough plant in Erdos, Inner Mongolia, in 2010. According to our information, the construction is currently on hold and full operation is expected in 2017 [46, 47].

Figure G-3 shows the locations of the seven CSP plants in China. Most of them are located in the in western and north-eastern regions of China, as the DNI in these areas can reach up to 2200-2300 kWh/(m^2 year) [48, 49].

Figure G-3: Locations of China's CSP projects.

Table G-2: National database of CSP projects under construction and operation in China.

CSP projects in China	1. CAS IEE –Yanqing-Parabolic plant	2. CGNPG-Delingha-Parabolic plant	3. Datang-Erdos-Parabolic plant	4. CAS IEE-Yanqing-Tower plant	5. Supcon-Delingha-Tower plant	6. Sanhua Heli-Wuhai-Dish plant	7. Huaneng-Nanshan-Fresnel plant
General information							
Location, Province	Yanqing, Beijing	Delingha, Qinghai	Erdos, Inner Mongolia	Yanqing, Beijing	Delingha, Qinghai	Wuhai, Inner Mongolia	Nanshan, Hainan
Operator	CAS IEE	CGNPG	Datang	CAS IEE	Supcon	Sanhua Heli	Huaneng
Project status: construction phase	since July 2014	construction completed	since September 2013	construction completed	construction completed	since July 2012	construction completed
Project status: operational phase	expected in 2015	Since July 2014	expected in 2017	Since July 2013	Since July 2013		Since November 2012
Technical information							
CSP technology variant	Parabolic Trough	Parabolic Trough	Parabolic Trough	Tower	Tower	Dish	Fresnel
Capacity (MW)	1	1	50	1	50	1	1.5
Project size	demonstration project	demonstration project	utility-scale project	demonstration project	utility-scale project	demonstration project	demonstration project
Direct normal insolation (DNI) (kWh/(m^2 yr)			1900	1900	1900	1900	
Electricity generation (MWh/yr)			138,700	1950	130,000	2000	
Capacity Factor			0.3167	0.2226	0.2968	0.2283	

Economic and financial information							
Economic Life (years)			25	25	25	25	
Depreciable life (years)			10	10	10	10	
Equipment Costs (RMB/kWh)			22422.4	27160	14035.2	31000	
Other costs (RMB/kWh)			6697.6	10000	5164.8	10000	
Total investment cost (RMB/kWh)			29120	37160	19200	41000	
O&M costs (RMB/kWh)			104	492	150	492	
Data collection and references							
Data from on-site interviews				X		X	
Press news	X	X			X		X
Project-specific reports and academic studies			X				
References in this study	[41]	[46, 47, 50]	[26]	[30-32]	[44, 45]	[35, 36]	[43]

G.4.2. Current electricity generation costs for different CSP technology variants in China

Table G-3 lists the current LCOE of four CSP projects in China with the default assumptions discussed in Section 3. We obtained sufficient data to carry out the LCOE calculation for four of the seven CSP plants. The current LCOE for the four different CSP plants falls in a range of 1.2-2.7 RMB/kWh (0.19-0.43 US$/kWh).

The 50 MW Supcon-Delingha-Tower plant maintains the lowest electricity generation costs in comparision with the other CSP projects. A major reason is the lower total investment and O&M costs per MW of capacity installed (economies of scale). Moreover possibility of preferential government policies and regulations might have contributed to the favorable land, equipment and construction costs of this project.

Table G-3: LCOE costs of different CSP projects.

CSP Project	LCOE($/kWh)	LCOE (RMB/kWh)
3 Datang-Erdos-Parabolic plant	1.71	0.27
4 CAS IEE-Yanqing-Tower plant	2.51	0.40
5 Supcon-Delingha-Tower plant	1.19	0.19
6 Sanhua Heli-Wuhai-Dish plant	2.71	0.43

G.4.3. Future CSP costs and sensitivity analysis

The "short-term best technology scenario" assumes an increase in the capacity factor from 0.22 to 0.3 and an overall investment cost reduction of 20% for the Datang-Erdos-Parabolic plant and 50% for the CAS IEE-Yanqing-Tower plant and the Sanhua Heli-Wuhai-Dish plant. The higher average capacity factor applied is in line with the US ISEGS plant. The decrease of total investment costs are based on the economies of scale from 1MW demonstration plants to 50MW utility-scale commercial plants. The future LCOE in the "short-term best technology scenario" could decline to up to 0.87 RMB/kWh for the Supcon-Delingha-Tower plant; up to 1.03 RMB/kWh for the Datang-Erdos-Parabolic plant; up to 1.12 RMB/kWh for the CAS IEE-Yanqing-Tower plant and up to 1.19 RMB/kWh for the Sanhua Heli-Wuhai-Dish plant.

The "scenario of mature thermal storage" assumes a capacity factor increase to 0.6, in the range of the 0.75 capacity factor of the new Gemasolar plant in Spain. Thermal storage is included here as technically and economically available in the long-term. We assume an increase of 10% in the overall investment costs, on top of the cost reductions in the "short-term best technology scenario". The future LCOE in the "scenario of mature thermal storage" could decline to up to 0.47 RMB/kWh (0.8 US$/kWh) for the Supcon-Delingha-Tower plant; up to 0.51 RMB/kWh for the Datang-Erdos-Parabolic plant; up to 0.56 RMB/kWh for the CAS IEE-Yanqing-Tower plant and up to 0.61 RMB/kWh for the Sanhua Heli-Wuhai-Dish plant.

Figure G-4 below shows the result ranges of our short-term and long-term sensitivity analysis for the four discussed CSP plants.

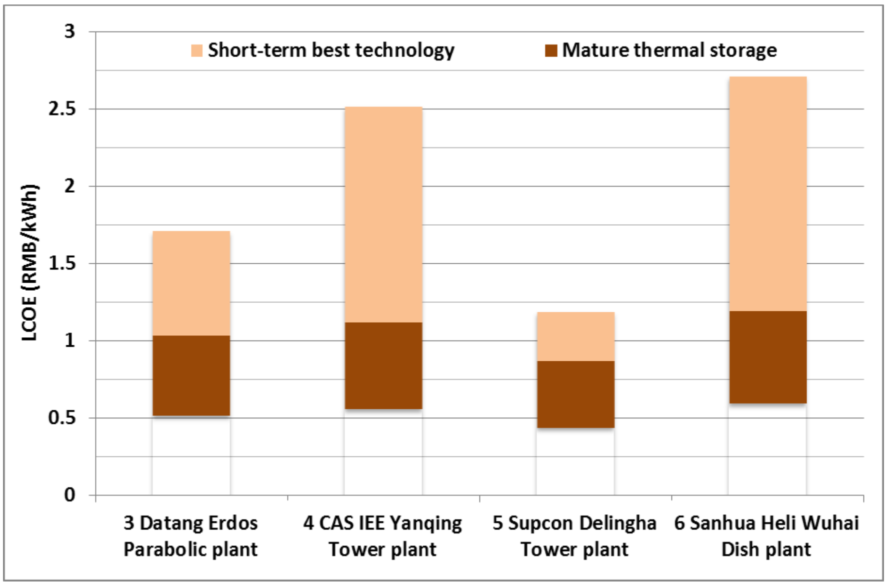

Figure G-4: Sensitivity analysis of Chinese CSP plants.

G.5. Discussion

G.5.1. Benchmarking of results

The LCOE of CSP varies significantly depending on the location, the size of the thermal storage and other particulars of the project. According to studies of CSP costs from other countries, parabolic trough systems are estimated to have an LCOE between 0.20-0.33 US$/kWh. CSP tower systems are estimated to have an LCOE between 0.16-0.27 US$/kWh [19-24] shown in Figure 5 and 6. The estimations are based on the CSP projects that have been commissioned or will come online in the near future in United States, South Africa, Morocco, and India. The calculated electricity generation costs of the Datang-Erdos-Parabolic plant and the Supcon-Delingha-Tower plant fall in the range of IRENA's recent CSP projections for China. The main reason why the CAS IEE-Yanqing-Tower plant is much more expensive is that this plant is still at a demonstration stage with 1 MW of capacity installed.

The 50 MW Supcon-Delingha-Tower plant, in comparison, has gained cost advantage over other tower CSP projects. The calculated LCOE of the Supcon-Delingha-Tower plant is close to the FIT of 1.2 RMB/kWh the National Development and Reform Commission (NDRC) issued. In August 2014, the project-specific Feed-in Tariff (FIT) of 1.2 RMB/kWh (US$0.23 in 2013 US dollar) for 50 MW Supcon-Delingha-Tower plant was approved by NDRC [51]. Though the national FIT of CSP will call for an evaluation of other demonstration projects, the approval of this FIT has already set a milestone of the CSP development in China.

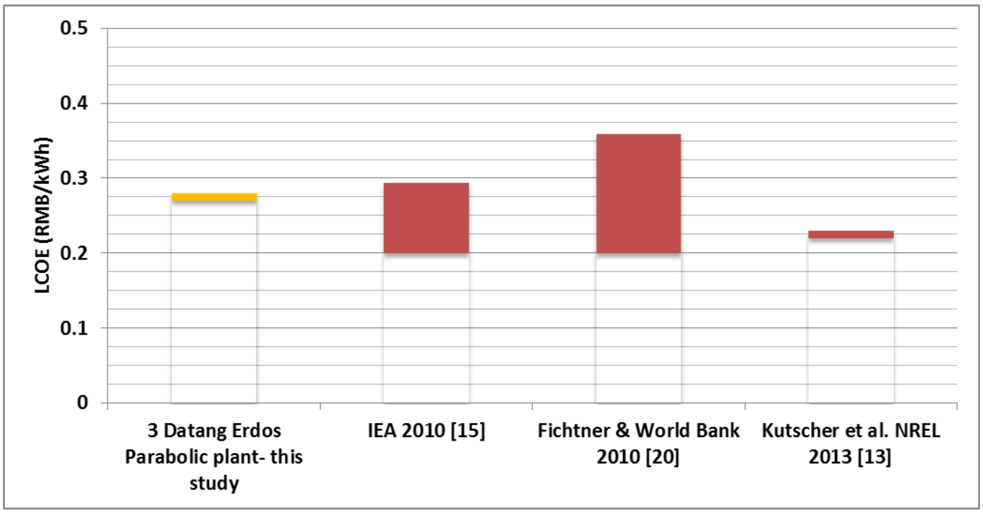

Figure G-5: LCOE benchmarking of parabolic trough CSP plants.

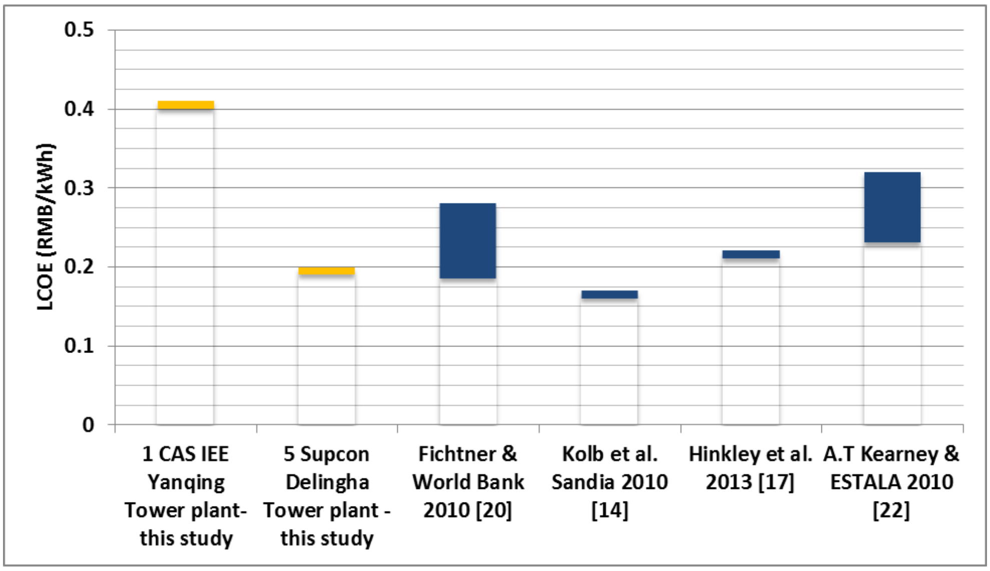

Figure G-6: LCOE benchmarking of tower CSP plants.

G.5.2. Drivers of future cost reduction for CSP in China

The CF is the key technical parameter that can be enhanced in the future, for instance by improved performance of receiver optics. Solar collector field, thermal storage system and the power block are the main drivers of total CSP investment costs in the short term. The reduction could occur with technological advancements, economic scaling and volume production. Comparing the demonstration project of the CAS IEE Yanqing Tower Plant with the commercial project of Supcon-Delingha-Tower plant, indicates that a total investment cost reduction of around 67% might be possible under economies of scale and a favorable investment conditions in China.

Presently thermal storage is still an expensive technology and most of commercial CSP plants choose to run either with short-term storage or be backed up with a natural gas power station. In the long-term thermal storage might become a future CSP standard, since continuous solar-base electricity generation with a thermal storage option is one of the main advantages that CSP has in comparison with the intermittent solar PV technology. The

Gemasolar CSP Tower Plant in Spain is the first operational CSP plant with thermal storage globally. So far it reported a storage capacity of 15 hours and a 24 days' non-stop power generation. The overall investment of this 20 MW CSP plant are quite high, about 230 million Euros [53].

There are currently no operational CSP plants with long-term thermal storage systems. Several new projects have however been announced recently. In April 2014 a 20 MW molten salt thermal storage system started construction in Jiangsu province, as announced by Jiangsu Sunhome New Energy Company [54]. In August 2014 a 1 million ton molten salt project started the construction in Delingha [55]. The future impact of heat storage on LCOE for CSP in China is very uncertain and needs to be recalculated later when data from operational plants become available.

G.5.3. Future steps of research and limitations

Since all the CSP projects in China are very new, it is difficult to obtain a complete set of technical, economic and financial data for every CSP. The key data of this study were therefore obtained by personal communications with different local CSP experts. A few data were also obtained from press news, such as CSPPLAZA, a major professional CSP industry website in China (in Chinese) and from previous studies, as discusses in the following paragraphs.

- For parabolic trough CSP technology many key parameters were unavailable for the 1 MW CAS IEE-Yanqing Parabolic plant, as it only started operation in July 2014. As the Clinton Climate Initiative evaluated the CSP costs of the 50 MW Datang-Erdos-Parabolic plant in Erdos recently [26], we rely on this set of data for the missing parameters.
- For tower CSP technology, there are two major operational projects in China, the 1 MW CAS IEE Yanqing Tower Plant and the 50 MW Supcon-Delingha Tower plant. Detailed plant data [30-32] and system simulation data [33] were obtained for the CAS IEE Yanqing Plant. Data for the Supcon-Delingha Tower plant were mainly obtained through press news and local CSP expert estimations.
- For dish CSP technology, the study is based on the 1 MW Sanhua Heli Wuhai Dish plant. Since the project has not been in full operation yet, the data obtained are partly from simulations [34]. Based on the on-site investigation [35] and the reference data from experts [36] in Sanhua, a specific simulation including dish collector, air receiver, heat exchanger and electricity generation was discussed and agreed upon.

A more precise CSP technology evaluation should be carried out in the future; once more operational data of these CSP plants or new CSP plants are available. Our results would also call for modification when CSP policies in China would change, as we base our results on the currently enacted solar PV and renewable energy policies.

G.6. Conclusion

Several new 100 MW parabolic trough CSP plants and 50 MW CSP tower plants are currently in the planning phase in China. The LCOE calculations for different CSP technology variants in different locations in China, as carried out in this study, will help to assess and compare the economic profitability of these new projects. Different from previous China-specific analysis that base on many assumptions and the data from other countries, this study assesses the economic feasibility of three CSP technology variants in China. A first benchmarking of CSP plants in China was carried out by calculating the LCOE of four typical CSP projects.

In comparison with CSP cost estimates in other countries, this study found that the utility-scale tower CSP plants in China have currently cost advantage over other CSP technology variants. The cost comparison between demonstration projects and the commercial projects reveals a huge potential of investment cost decline. Our sensitivity analysis on future LCOE for CSP in China indicates that tower CSP would be the short-term best CSP technology with the lowest LCOE of 0.87 RMB/kWh (0.14 US$/kWh). In the longer term tower CSP with mature thermal storage systems could achieve a LCOE decrease of up to 0.47 RMB/kWh (0.08 US$/kWh). This holds if we assume that the total investment costs would be managed well, that CSP technologies installed in China would be in line with the globally best available CSP technologies, and that China continues a favorable set of CSP investment conditions and regulations. Based on our expert interviews, tower CSP might also be the most advantageous CSP technology for China as a high share of local content manufacturing (self-developed) could be achieved.

Acknowledgment

The authors are very grateful for the immense support and personal assistance from Wang Zhifeng (President of the National Solar Thermal Energy Alliance, China); Liu Xiaobing (Secretary of the National Solar Thermal Energy Alliance, China); Yu Qiang (Research Associate of the Chinese Academy of Sciences Institute of Electrical Engineering, China); Li Bin (Head of the NDRC energy department, China); Zou Jiang (Senior Engineer of Sanhua Group, China); and Zhang Yanguo (Professor of the Tsinghua University Thermal Engineering Department, China). We acknowledge the generous financial support received from the following sources: the Ministry of Science and Technology of China and Rio Tinto through the Tsinghua University Institute for Energy, Environment, and Economy; Eni S.p.A. Italy, ICF International, and Royal Dutch Shell through the MIT Tsinghua University China Energy and Climate Project; and the Sino-Danish Centre for Education and Research through the Technical University of Denmark.

Appendix G-A: LCOE model

Net Present Value (NPV)-based model

(1) $\mathrm{NPV} = \sum_{i=1}^{N} \mathrm{Cash(i)} \cdot (1 + \mathrm{IRR})^{-i}$

where

NPV is the net cash value;

IRR is the internal rate of return, which is equal to the discount rate when the NPV is 0;

N is the total years of the project period;

Cash(i) is the cash flow in year i;

(2)

$$\mathrm{Cash(i)} = \mathrm{Revenue(i)} + \mathrm{Debt(i)} - \mathrm{CapitalCost(i)} - \mathrm{O\&MCost(i)} - \mathrm{Loanpayment(i)} - \mathrm{Tax(i)}$$

Where $\mathrm{Revenue(i)} = \mathrm{Q(i)} \cdot \mathrm{P}$

P is the LCOE price, which is assumed fixed for the whole economic life;

$\mathrm{Q(i)}$ is the annual electricity generation;

(3) $\mathrm{Q(i)} = \begin{cases} 0, \mathrm{i} = 1,2 \\ 8760 \cdot \mathrm{CF}, \mathrm{i} = 3 - 23 \end{cases}$

(4) $\mathrm{Debt(i)} = \begin{cases} 0.7\mathrm{CapitalCost}, \ \mathrm{i} = 2 \\ 0, \mathrm{i} \neq 2 \end{cases}$

(5) $\mathrm{CapitalCost(i)} = \begin{cases} 0.3\mathrm{CapitalCost}, \mathrm{i} = 1 \\ 0.7\mathrm{CapitalCost}, \mathrm{i} = 2 \\ 0, \mathrm{i} > 2 \end{cases}$

(6) $\mathrm{Loanpayment(i)} = \frac{\mathrm{Debt(2)} \cdot \mathrm{r} \cdot (1+\mathrm{r})^{20}}{(1+\mathrm{r})^{20} - 1}, \mathrm{t} = 3 - 23, \mathrm{r} = 5.95\%$

(7) $\mathrm{Tax(i)} = \mathrm{VAT(i)} + \mathrm{EIT(i)} + \mathrm{Surtax(i)}$

where,

the value added tax in year i: (8) $\mathrm{VAT(i)} = \frac{\mathrm{Revenue(i)} \cdot 0.17 \cdot 0.5}{1.17}$

the tax surcharge in year i: (9) $\mathrm{Surtax(i)} = 0.1 \cdot \mathrm{VAT(i)}$

the enterprise income tax in year i : (10) $\mathrm{EIT(i)} = \begin{cases} 0, \mathrm{i} = 1 - 5 \\ 0.125\mathrm{IBT(i)}, \mathrm{i} = 6 - 8 \\ 0.25\mathrm{IBT(i)}, \mathrm{i} \geq 9 \end{cases}$

where

(11) $\mathrm{IBT(i)} = \mathrm{Revenue(i)} - \mathrm{InterestPayment(i)} - \mathrm{O\&Mcost(i)} - \mathrm{Depreciation(i)}$

where

(12) $\mathrm{InterestPayment(i)} = \mathrm{Principal(i-1)} \cdot \mathrm{r}, \mathrm{i} = 3 - 23$

(13)$\mathrm{Principal(i-1)} = \begin{cases} \mathrm{Debt(2)}, \mathrm{i} = 3 \\ \mathrm{Principal(i-2)} \cdot (1 + \mathrm{r}) - \mathrm{Loanpayment(i)}, \mathrm{i} = 4 - 23 \end{cases}$

(14) $\mathrm{Depreciation(i)} = \frac{\mathrm{CapitalCost}}{10}, \mathrm{i} = 3 - 13$

We use the straight-line method to calculate the depreciation. The useful economic life is assumed to be 25 years.

Appendix G-B: Detailed costs of major CSP projects

Costs (1,000 RMB)	Datang-Erdos-Parabolic plant	CAS IEE-Yanqing-Tower plant	Supcon-Delingha-Tower plant[1]	Sanhua Heli-Wuhai-Dish plant
Equipment Costs	1121120	27160	701760	31000
Solar Collection System	728000	20000		20000
Thermal Storage System	160160	1810		
Heat Collection System	160160	1850		8000
Power Block	72800	3500		3000
Other costs	334880	10000	258240	10000
Control System	72800	1500		C
Land	58240	500		500
Construction	43680	5000		5000
Other services and management	160160	3000		3000
Total investment cost	1456000	37160	960000	41000
Labor	2700	720	2700	720
Materials	10000	200	10000	200
Unpredictable costs	1800	40	1800	40
Overall O&M costs	14500	960	14500	960
References	[26, 4]	[45-]	[30; 31]	[49-51]

[1] Total investment cost of Supcon-Delingha-Tower plant is acquired online. Equipment costs and other costs are calculated by the reference of the 1MW Yanqing Tower Plant.

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